Assembly and Installation of an Engine Control Module

HÄMEEN AMMATTIKORKEAKOULU
HÄME UNIVERSITY OF APPLIED SCIENCES

Bachelor's thesis

HAMK Valkeakoski
Automation and Electrical Engineering
2018-2019

Apolinarii Sorokin

Hämeen ammattikorkeakoulu
Häme University of Applied Sciences

Automation and Electrical Engineering
Valkeakoski

Author	Apolinarii Sorokin	**Year** 2019
Title	Assembly and Installation of an Engine Control Module	
Supervisor(s)	Rainle Lehto, Juhani Hentonen	

ABSTRACT

The main goal of this thesis was to study and review the operating principles of Internal Combustion Engines Control Systems. After this background research the engine control module was built using electrical components and open source Megasquirt printed circuit board. The theoretical part of the thesis is focused on engine management technologies and their applications. The practical part of work started from the construction of the engine control module and it continued with connecting the module to the BMW 3 Series E36 to replace the standard Bosch DME Motronic control Unit. Installation of the system allowed switching the engine from natural aspiration to forced induction using the turbocharger.

Keywords ECU, EFI, Engine Control, Megasquirt, Internal Combustion.

Pages 40 pages including appendices 2 pages

CONTENTS

1. INTRODUCTION

This project was aimed at modernizing the engine control system of an old car and to explore the possibilities of the open source Megasquirt engine control module. 1998 BMW 320 E36 was bought as a donor for that project.
As a result of this project an electronic engine control system which supported fully sequential injection and sequential ignition and all different kinds of modern engine control features was built. Also, it will be possible to increase the power of the car using the Turbo- or Super- chargers in the future according to the plan created during the project.

First of all, in the second chapter, the evolution of engine control systems is reviewed, from old fully mechanical systems to modern EFI systems and their details. Inputs and Outputs of these systems and their algorithms is described, the difference between racing and civilian applications is evaluated. General information is followed by a review of the system, used in the donor vehicle, in a very detailed manner. Described chapter will also review the working principle of each sensor, used in particular case. In chapter 3 the Megasquirt control module, its history, schematics and building process and more will be described. Chapter 2 is about wiring and all the work, which will be done on donor vehicle. In the Chapter 5 the process of vehicles tuning after the installation of the Megasquirt control module is described.

1 FUEL INJECTION IN GENERAL

1.1 Internal Combustion

1.1.1 History of Fuel Injection Control

In the past a carburator was used to mix the air with fuel and to deliver the mixture to the combustion chamber. The system was completely mechanical and had a lot of different limitations. First of all, carburator systems are gravity-dependent, which means they are not really suitable for extreme applications like racing or aviation. The second main reason why this kind of systems are left in the past is the lack of a closed loop control, which is needed for such a sophisticated system like an internal combustion engine. The absence of closed loop control leads to impossibility to tune carburators accurately enough to meet adequate emissions requirements and to perform at optimal performance along the whole operating range of the engine. It is not possible to tune the AFR (Air to Fuel Ratio) properly, which means that carburator equipped engines are less efficient in both power output and fuel consumption.

1.1.2 History of Ignition Timing Control

To burn fuel, in the past, distributor systems were used, which is also, a fully mechanical system. Distributor itself is very simple. Ignition coil which is connected to the moving contact, called rotor, which is located on the end of the camshaft and has 4 different contacts around it. When it comes in touch with the specific contact, voltage from the coil is sent to the corresponding spark plug. Just like carburators it was a very limited system. The user was not able to optimize ignition advance angle along the operation range of the engine. Ignition timing was set once by changing the mounting angle of the distributor rotor.

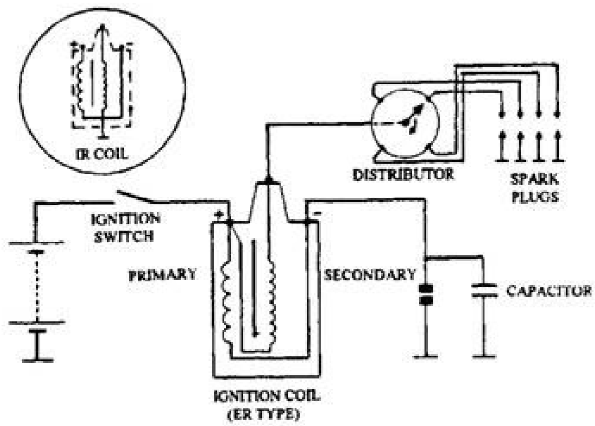


Figure 1. Ignition Distributor Diagram. What-When-How (2018).

1.1.3 Ignition Advance and AFR

Why it is needed to control the Ignition Timing and Air to Fuel Ratio? These are the two key parameters, which make modern engines both efficient and ecological.

1.1.3.1. Ignition Timing

When talking about ignition timing we mean spark advance. Spark advance is the time before TDC (top dead centre) when the spark is initiated. It is expressed in degrees of crankshaft rotation relative to TDC (fig 2). Until some point, called MBT (Mean Best Torque) increasing the Ignition Advance will increase the power output of the engine, but also increase the HC (Hydrocarbon) and NOx (Nitrogen Oxide) emissions at the same time. After reaching the MBT, further increase in ignition advance angle will lead to effect known as “engine knock” or “spark knock”. Engine knock occurs because fuel starts to burn in uneven pockets instead of uniform bursts, and it is very destructive for the engine. It is possible to detect the “engine knock” using the knock sensor, it will give us a possibility to reduce the advance angle after knock has been detected, which will prevent the engine from failing. Also, further increase in ignition advance angle after reaching the MBT will cause power output to decrease dramatically. It is very important to have a control over ignition timing and tune it properly in order to get high power output without damaging the engine.

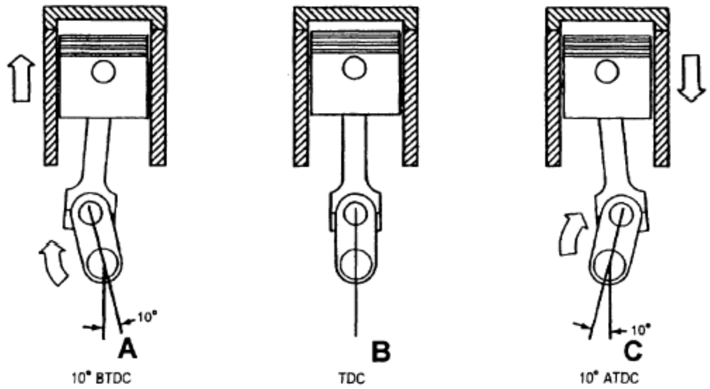


Figure 2. TDC diagram. WayBuilder (2015).

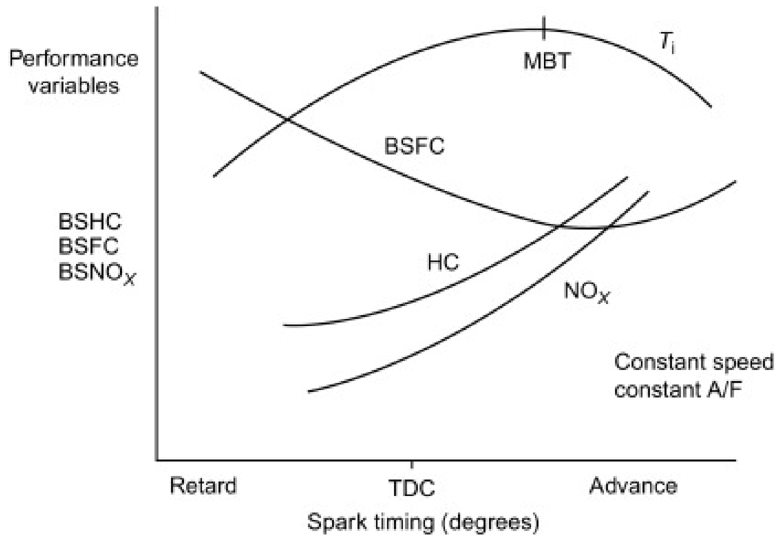


Figure 3. Effects of ignition timing graph. Ribbens W.B. (2017)

1.1.3.2. Air to Fuel Ratio

AFR (Air to Fuel Ratio) is the second most important parameter in engine control. This parameter is calculated based on residual oxygen in exhaust gases and represents the quality of mixture, burning inside the engine. Mixture could be either lean, stoichiometric and rich. AFR scope is different for each type of fuel. While talking about gasoline powered engines - stoichiometric mixture is 14.7:1, which means 14.7 grams of air are mixed with 1 gram of fuel. Stoichiometric mixture is different for each type of fuel and while engine is tuned to run on stoichiometric mixture, it will burn 100% of the air and fuel in the combustion chamber (in ideal theoretical situation) and produce a minimal amount of emissions. It is a very important parameter in engine tuning, both for civilian and racing applications. In civilian car manufacturers need the lowest emissions with appropriate power and fuel consumption, while in racing car it is important to have enough fuel to run in either stoichiometric or rich areas to avoid the "engine knock" while producing the maximum power possible. AFR could be measured using Wideband lambda sensor its application and principals are going to be described in paragraph 2.3.4.7.

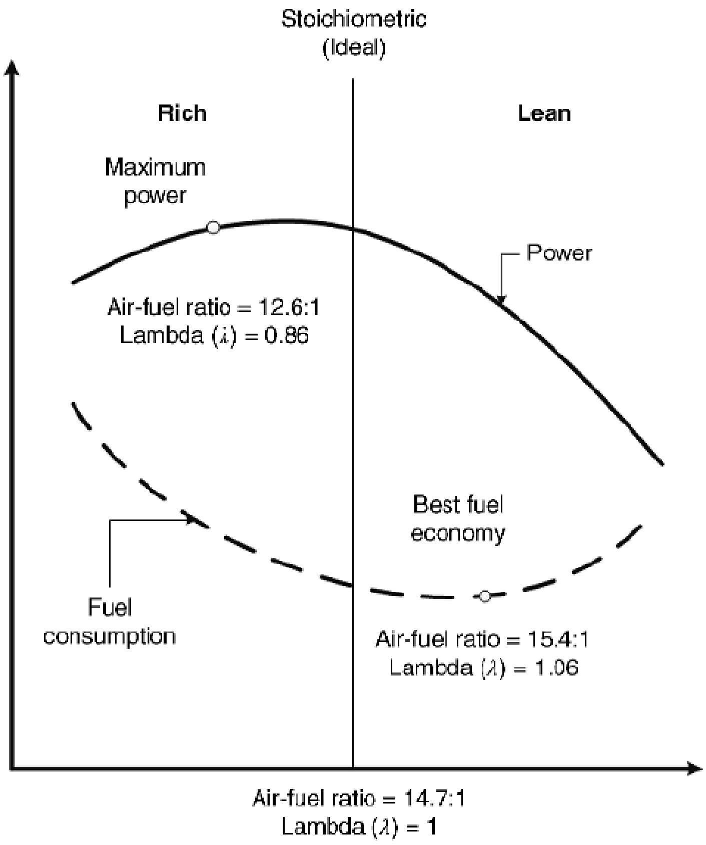


Figure 4. Mixture quality effects graph. Engineering ToolBox (2003)

1.2 **EFI Systems**

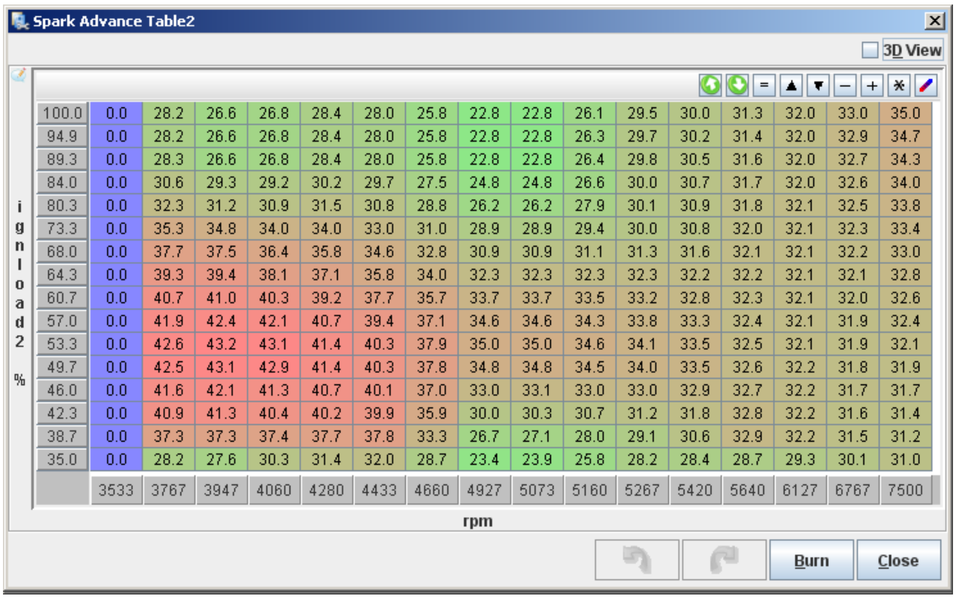
EFI system is the modern way of controlling the engine. Since 1955, while Bosch have successfully tested their Motronic fuel injection system, all the automotive corporations started to replace carburettors and ignition distributors with Electronic Fuel Injection systems. In year 1990 more than 90% of the vehicles were already equipped with EFI systems instead of old-fashioned mechanical solutions.

1.2.1 Inputs and Outputs

Just like any other automated system, EFI systems have Inputs and Outputs, which they have to process. Number of both inputs and outputs depends on the engine and its equipment. The I/Os used in that particular project is described in detail in chapter 2.3.

1.2.2 Algorithm

After ECU have received all the information needed, it needs to process it according to the user's preferences to send the proper signal to the outputs. All the main settings inside the ECU are made by user via editing maps, and therefore the process of tuning is called mapping. Map simply is a 2D table with resolution from 10x10 cells for first ever ECU Bosch Motronic up to 30x30 for the best available racing ECUs.
Concluded from the previous paragraph, there are two main outputs: ignition and injection.
To control ignition timing, Megasquirt uses 16x16 ignition map.
It has MAP(Manifold Absolute Pressure) on the Y-axis and engines RPM(Revolutions per Minute) on the X-axis and user makes inputs in cells during the process of tuning, which will be covered in details in paragraph 6. Therefore, based on user input to the Spark Advance Map and according to 3 parameters (MAP, RPM and Crankshaft Position) ECU sends ignition signal to the ignition drivers.



Spark Advance Table2

ignload2 %	3533	3767	3947	4060	4280	4433	4660	4927	5073	5160	5267	5420	5640	6127	6767	7500
100.0	0.0	28.2	26.6	26.8	28.4	28.0	25.8	22.8	22.8	26.1	29.5	30.0	31.3	32.0	33.0	35.0
94.9	0.0	28.2	26.6	26.8	28.4	28.0	25.8	22.8	22.8	26.3	29.7	30.2	31.4	32.0	32.9	34.7
89.3	0.0	28.3	26.6	26.8	28.4	28.0	25.8	22.8	22.8	26.4	29.8	30.5	31.6	32.0	32.7	34.3
84.0	0.0	30.6	29.3	29.2	30.2	29.7	27.5	24.8	24.8	26.6	30.0	30.7	31.7	32.0	32.6	34.0
80.3	0.0	32.3	31.2	30.9	31.5	30.8	28.8	26.2	26.2	27.9	30.1	30.9	31.8	32.1	32.5	33.8
73.3	0.0	35.3	34.8	34.0	34.0	33.0	31.0	28.9	28.9	29.4	30.0	30.8	32.0	32.1	32.3	33.4
68.0	0.0	37.7	37.5	36.4	35.8	34.6	32.8	30.9	30.9	31.1	31.3	31.6	32.1	32.1	32.2	33.0
64.3	0.0	39.3	39.4	38.1	37.1	35.8	34.0	32.3	32.3	32.3	32.3	32.2	32.2	32.1	32.1	32.8
60.7	0.0	40.7	41.0	40.3	39.2	37.7	35.7	33.7	33.7	33.5	33.2	32.8	32.3	32.1	32.0	32.6
57.0	0.0	41.9	42.4	42.1	40.7	39.4	37.1	34.6	34.6	34.3	33.8	33.3	32.4	32.1	31.9	32.4
53.3	0.0	42.6	43.2	43.1	41.4	40.3	37.9	35.0	35.0	34.6	34.1	33.5	32.5	32.1	31.9	32.1
49.7	0.0	42.5	43.1	42.9	41.4	40.3	37.8	34.8	34.8	34.5	34.0	33.5	32.6	32.2	31.8	31.9
46.0	0.0	41.6	42.1	41.3	40.7	40.1	37.0	33.0	33.1	33.0	33.0	32.9	32.7	32.2	31.7	31.7
42.3	0.0	40.9	41.3	40.4	40.2	39.9	35.9	30.0	30.3	30.7	31.2	31.8	32.8	32.2	31.6	31.4
38.7	0.0	37.3	37.3	37.4	37.7	37.8	33.3	26.7	27.1	28.0	29.1	30.6	32.9	32.2	31.5	31.2
35.0	0.0	28.2	27.6	30.3	31.4	32.0	28.7	23.4	23.9	25.8	28.2	28.4	28.7	29.3	30.1	31.0

rpm

Figure 5. Spark advance table.

Algorithm to control the injection is more complex. There are two main tables. VE (Volumetric Efficiency) and AFR(Air to Fuel Ratio). First one is the most important, while second one, in most of the racing applications, is used as a reference table, to make corrections to the first one. Volumetric efficiency is the ratio of volumetric mass density of the fuel mixture fed into the cylinders at normal (atmospheric) pressure during one engine stroke to the volumetric mass density of the same volume of air in the intake manifold. Formulas used to calculate the VE are quite complex and i am going to cover them in paragraph 6. Just like any other map, VE map has MAP on Y-axis and RPM on X-axis. When starting to work with the engine, user first calculates the VE map using special calculator (covered in paragraph 6) and after that makes fine-tune corrections.

"VE Table 1"

fuel load % \ rpm	700	1066	1480	1940	2453	2900	3380	3893	4406	4860	5333	5840	6280	6773	7100	7800
104.0	98.0	98.7	99.5	100.2	100.9	101.0	100.6	100.0	100.0	98.8	97.3	95.9	94.4	92.4	91.0	88.0
98.0	92.0	92.2	92.4	92.6	92.7	92.8	93.3	94.1	94.6	94.0	91.8	88.3	85.7	84.2	83.5	82.0
92.0	85.0	85.0	85.0	85.0	85.0	85.0	86.2	88.0	88.0	87.4	85.7	82.8	80.6	78.9	78.0	76.5
86.0	77.5	77.5	77.5	77.5	77.5	77.5	78.8	80.7	80.1	79.4	78.3	76.9	75.4	73.4	72.0	70.0
80.0	70.0	70.0	70.0	70.0	70.0	70.0	70.4	71.0	71.0	70.4	69.3	67.9	66.4	64.4	63.0	61.0
74.0	62.5	62.5	62.5	62.5	62.5	62.5	64.7	67.9	67.4	66.7	65.6	64.2	63.3	61.4	60.0	58.0
68.0	55.0	55.0	55.0	55.0	55.0	55.0	57.8	61.9	61.6	61.2	60.7	60.0	59.6	58.7	58.0	56.0
62.0	50.0	49.1	48.2	47.5	47.5	48.0	51.3	55.8	55.8	55.6	55.3	55.0	54.6	54.2	54.0	52.0
57.0	50.0	46.8	43.6	41.3	41.3	43.0	47.4	52.6	52.6	52.1	51.2	49.9	48.6	47.3	46.5	44.5
52.0	50.0	46.3	42.7	40.0	40.0	41.1	44.5	48.7	48.7	48.1	47.2	46.2	44.7	43.3	42.3	41.0
47.0	50.0	46.0	47.0	47.0	40.0	40.4	42.6	45.6	46.1	45.7	44.9	44.1	42.7	41.4	40.6	40.0
41.0	54.0	54.0	53.0	51.0	44.6	39.8	41.0	43.0	44.5	44.2	43.5	42.7	41.4	40.5	40.0	40.0
37.0	58.0	57.0	55.2	53.6	53.0	42.3	40.0	41.7	43.8	43.6	42.8	42.1	41.2	40.5	40.0	40.0
31.0	57.0	61.7	57.6	56.6	56.0	47.7	39.2	40.9	43.5	43.4	42.7	41.9	41.2	40.5	40.0	40.0
28.0	55.2	63.5	62.4	58.0	59.6	58.8	45.9	40.5	43.5	43.4	42.7	41.9	41.2	40.5	40.0	40.0
20.0	41.0	56.4	57.9	49.2	47.9	49.1	39.2	40.5	43.5	43.4	42.7	41.9	41.2	40.5	40.0	40.0

Figure 6. VE table.

AFR table, as mentioned above, is mostly the reference table, which might even be ignored by the ECU, if user has disabled AFR closed-loop control. AFR closed-loop control means, that the ECU makes correction to the VE table, if reading from Wideband Lambda sensor does not match the AFR table. In civilian applications regular lambda sensor is used instead of wideband, which means it cannot detect the AFR, it can only detect if the mixture is stoichiometric at the moment. Another type of closed-loop control is used in civilian cars, ECU always tries to keep lambda as close to 1.0 (stoichiometric mixture) as possible, ensuring lowest emissions possible. In Megasquirt AFR map is quite important, because it supports the closed-loop control and also auto-tune feature, which means that VE table can not only be corrected on-the-go, but also might be tuned automatically by the controller, using AFR map as a reference map. AFR map in Megasquirt has smaller resolution compared to 2 tables mentioned above, it is only 12x12 cells.

AFR Table 1

afrload1 % \ rpm	500	800	1300	1900	2500	3200	3800	4500	5100	5700	6500	7500
200.0	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5
170.0	11.8	11.8	11.8	11.8	11.8	11.7	11.8	11.8	11.8	11.8	11.7	11.7
140.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	11.9	11.8
125.0	12.3	12.3	12.3	12.3	12.3	12.3	12.2	12.2	12.2	12.4	12.3	12.2
110.0	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.0	12.7	12.7	12.5
95.0	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.3	13.1	12.9	12.8
85.0	14.4	14.4	14.5	14.5	14.5	14.5	14.3	13.9	13.7	13.5	13.4	13.5
70.0	14.7	14.7	14.9	14.9	14.9	14.9	14.3	13.9	13.8	13.6	13.5	13.5
60.0	14.7	14.7	14.9	14.9	14.9	14.9	14.3	14.0	13.8	13.7	13.6	13.5
45.0	14.7	14.7	14.7	14.9	14.9	14.9	14.3	14.0	13.8	13.7	13.6	13.5
35.0	14.7	14.7	14.7	14.9	14.9	14.9	14.3	14.0	13.8	13.7	13.6	13.5
20.0	14.7	14.7	14.7	14.9	14.9	14.9	14.3	14.0	13.8	13.7	13.6	13.5

Figure 7. AFR table.

1.2.3 Racing EFI Systems compared to Civilian

Some of the differences between civilian and racing control modules have already been mentioned in previous paragraphs, and in that paragraph, everything will be summed up and described in detail.
Civilian ECUs are designed once and to suit every driver's needs and to match with the modern emission standards at the same time. They are a lot more complex in terms of emissions control, but loose dramatically in terms of fine-tuning and different racing outputs control. Modern civilian ECU's have an ability to control all kinds of emissions reducing mechanism, such as EGRV (Exhaust Gas Recirculation Valve), DPF(Diesel Particular Filter), Catalytic Converter and ADBlue. At the same time, on average they have a map resolution of only 10x10 cells, and no ability for tuning (tuned once on the factory), which makes them quite rough. Modern racing ECUs, on the other hand, have a huge resolution (from 16x16 up to 30x30), and ability to control unlimited number of custom outputs (It could be either eco-friendly EGR or additional Methanol injection for racing purposes). Also, it is possible to tune them in real time, which means it is possible to achieve the best results possible.

1.3 **Systems Used in The Project**

In that paragraph the system, used in donor vehicle, which is controlled by the ECU is going to be described. Some of the factory components were replaced to match the performance requirements. First of all, the MAF (Mass air Flow) sensor was replaced with a MAP (Mass Air Pressure), because MAF cannot handle pressure, generated by turbocharger, which is going to be present in described application. The MAF sensor is mounted before the throttle body sensor from factory on this vehicle, while the MAP sensor is located inside the Megasquirt ECU. Detailed diagram of modified system is presented in fig 8.

1.3.1 Air System

In that paragraph the components of engine's air supply system are going to be reviewed and described. The system was upgraded with a turbocharger and intercooler. Also, as mentioned above, MAF sensor was excluded from the system.

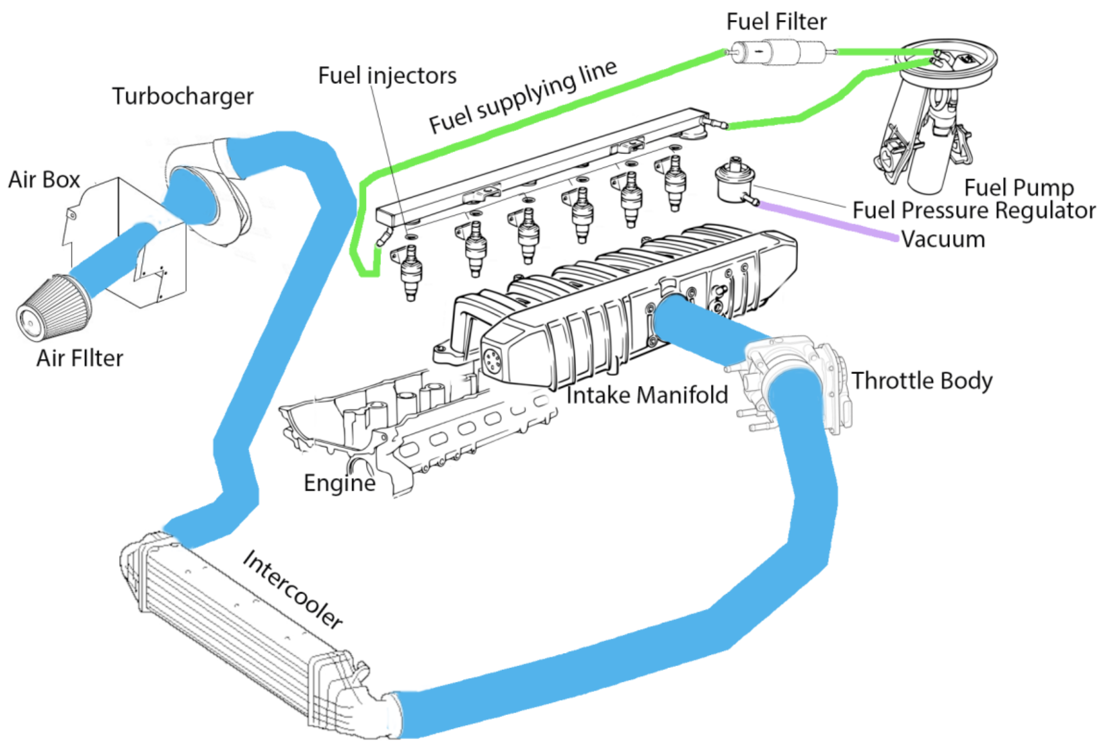


Figure 8. Air system diagram.

1.3.1.1. Intake Manifold

Intake manifold is an engine component responsible for delivering combustion mixture to the engine head. The main purpose of it is to evenly distribute the mixture to each intake port. In considered case, intake manifold is also used as a mount for throttle body and fuel injectors. Intake manifold is a part of air supply system, so the port diameter matters a lot in terms of engine's performance. To increase the performance of the vehicle, it is not enough to just add a turbocharger to the system, it is also needed to ensure that there is a good air flow throughout the system. The factory manifold from 2.0 engine with cross sectional port area of 10.00 cm2 was changed to 2.5 engine manifold equipped with 13.75 cm2 ports. Cylinder head ports were also increased to exactly match the intake manifold port profile to ensure the least air resistance possible.

1.3.1.2. Throttle Body

Throttle body is a very simple, in researched case fully mechanical component of air intake system. It is just a spring-loaded butterfly valve, connected with an accelerator pedal using a throttle cable, which opens and closes according to driver's wish and regulates the amount of air which goes into the engine. In modern applications, electronic throttle body systems are used in order to have a full control on smoothness of a unit and have an ability to add such features as cruise control, which would be pretty hard to implement using the mechanical based unit. Even with mechanical units, it is very important to have an ability to monitor the status of the valve and it will be done using the built in TPS (Throttle Position Sensor), it is necessary value to calculate the amount of fuel, which will enter the cylinder. The throttle valve from standard 2.0-liter engine had to be changed to the 2.5-liter option in order to maintain the flow suitable for the bigger intake manifold.

1.3.1.3. Turbocharger

There are many ways of increasing the engine's performance, in considered case forced induction was chosen, because it is interesting from scientific point of view. The most exciting fact about this method is ”energy recycle”. The turbocharger operation is based on using the exhaust gas flow to accelerate the wheel of the “hot” part of the turbocharger, which is called compressor. Therefore, turbine wheel starts to rotate pushing the excessive air into the intake system, because the compressor and turbine (“hot” and “cold”) parts of the system are mounted on the same shaft, supported by the variety types of bearing inside the casing. By allowing more air to enter the combustion chamber, there is a possibility to inject more fuel and as a result a huge rise of the power output is gained.

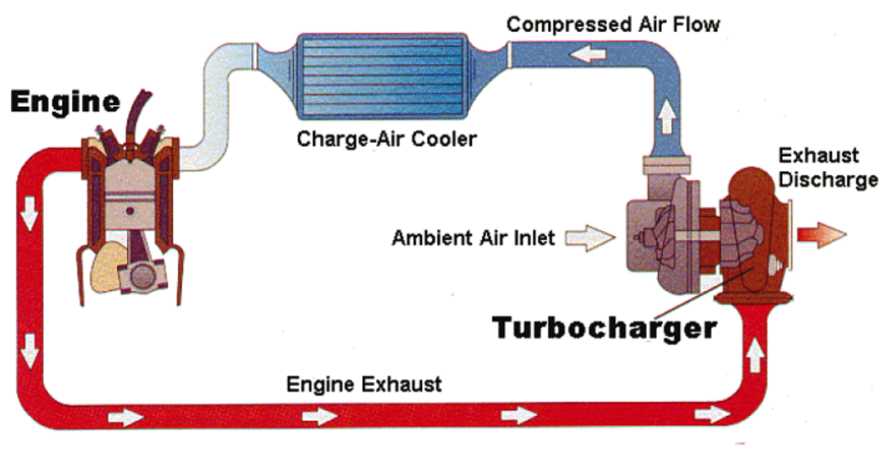


Figure 9. Turbocharger diagram. HowStuffWorks (2014).

But there are a lot of different turbochargers available on the market and for that project it is needed to choose one, ideal for the application. After reviewing similar projects the Garrett GT2871R turbocharger was chosen. It will allow to run full boost (maximum intake pressure) at 3000 RPM and according to calculations it will increase the power and torque output from 150 HP and 190 NM up to 390 HP and 510 NM.

1.3.1.4. Intercooler

Intercooler is a necessary component of an air intake system of a forced induction-based engine. It is responsible for removing the waste heat in a gas, generated by the process of gas compression. Compression causes a huge rise in the gas's internal energy and consequently increases its temperature and reduces the density. Intercooler is placed right after the compressor and acts as a heat exchanger between the ambient air and air inside the intake system.

1.3.1.5. Air Filter

Air filter is a first component of an air intake system and is used to filter the air from the dust and other waste in order to increase the engines lifespan. This component was also changed and placed inside the custom Air Box for the two main reasons. First of all, the turbocharger is now mounted on the place, where the massive air filter casing was mounted from the factory, so there is a lack of space under the hood. Second reason is the increased air flow, which requires the usage of the "zero-resistance" air filter. Performance air filters flow up to 65% more air than standard therefore they do not create any bung effect as a standard filter.

1.3.1.6. Air Box

To get the best power output it is necessary to maintain the intake air temperature as low as possible. Such a component as an intercooler was described above, but it is not enough if the air is going to be initially taken from the hot place. Forced induction engines produce quite a lot of heat, during the normal operation exhaust gas temperature is usually above 500 degrees Celsius and average temperature inside the engine compartment is rarely below 200 degrees. That is the reason why in the particular case a metal cold air intake box which is located on the edge of the engine compartment and is surrounded with thermal insulation.

1.3.2 Fuel System

In that paragraph the components of engines fuel supply system are going to be reviewed and described. The system was upgraded to meet the performance requirements.

1.3.2.1. Fuel Pump

Fuel pump is the first component of any fuel supply system. This component is located inside the fuel tank and is needed to supply the constant fuel pressure to the fuel rail, where the fuel injectors are mounted. In particular case electric type fuel pump was used from the factory and is used after the fuel supply system upgrade. The only difference between the old and new unit is efficiency. BMW OEM (Original Design Manufacturer) Fuel pump was able to supply up to 110 liters per hour, while the new Walbro GST450 is able to supply 450 liters per hour. The reason why such a huge rise is needed is the increased flow of fuel injectors, which are going to be described in paragraph 2.3.2.4.

1.3.2.2. Fuel Filter

Basic component of fuel supply system, which is needed to prevent any kind of waste to get into the fuel supply lines. It is mounted right after the fuel pump and does not require any upgrade, because OEM filter has a sufficient flow for my application (600 l/h according to BMW Repair Manual)

1.3.2.3. Fuel Pressure Regulator

Fuel pressure regulator is a very important component of a fuel supply system, which is used to maintain a stable pressure inside the fuel rail, even during the dramatic fuel demand changes. It controls the fuel pressure by adjusting the amount of fuel going back to the fuel tank from the pressurized fuel rail. In considered case the unit is fully mechanical and consists of a diaphragm, connected to the bypass valve. When the pressure comes to the diaphragm from intake manifold (engine operates at wide open throttle) the bypass valve gets closed and all the fuel pumped to the fuel rail remains there. When the engine is operating in the idle or cruise areas, spring pushes the diaphragm down and reduces the amount of excessive fuel. Desired pressure can be changed by changing the spring inside the unit. OEM spring maintains the pressure inside the fuel rail roughly at 3.5 bar.

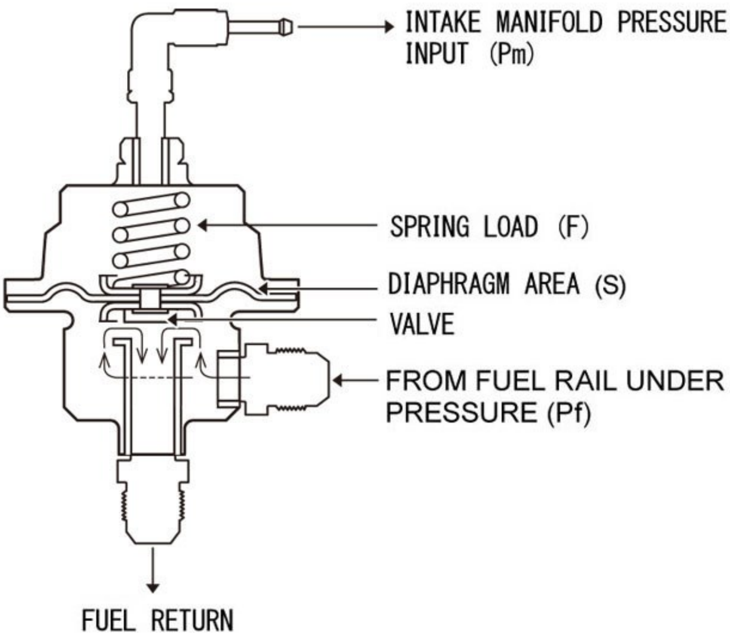


Figure 11. Fuel pressure control valve diagram. VaporWorx (2016).

1.3.2.4. Fuel Injectors

Fuel injectors are the main components of fuel supply system, which are responsible for the fuel injection inside the intake manifold ports. Operation principle of fuel injectors is simple, it is just an electrically controlled spring-loaded valve, which is capable of opening and closing many times per second. When the signal comes to the injector, an electronic magnet moves the plunger and allows the fuel to flow through the injector’s nozzle. Nozzle is made to atomize the fuel, so that it can burn easily. The amount of fuel flowing through is determined by the amount of time injector stays open. It is controlled by the ECU using the PWM (Pulse Width Modulation)

It is very important to choose the proper injectors when increasing the engines performance. Fuel injectors have only one characteristic and it is the maximum flow, which is calculated in cubic centimeters per minute. OEM fuel injectors on the donor vehicle were able to supply up to 170 cm^3/min and they have been replaced with BOSCH 650 cc/m injectors, which will be able to provide enough fuel for the application.

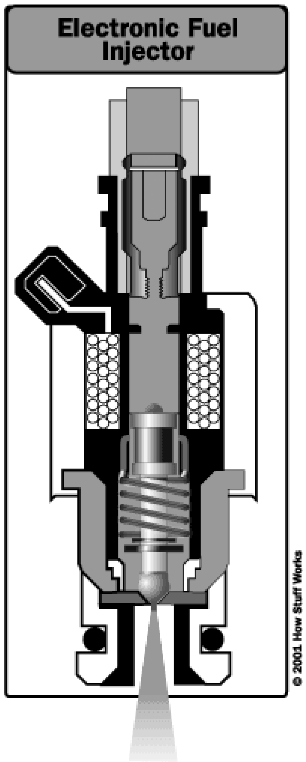


Figure 12. Fuel injector diagram. HowStuffWorks (2017).

1.3.3 Standard Electronic System (ECU)

The donor vehicle was equipped with Bosch DME Motronic 3.1 System. Bosch DME Motronic 3.1 was the most advanced ECU at the time it was produced and installed on the donor vehicle, and it is still competitive with the modern civilian ECUs. It featured 12x12 map resolution, online tuning, so almost everything needed to match my performance requirements. The main problem for forced induction application was the MAF-based air calculation, narrowband lambda monitoring and lack of such a racing features like launch control, anti-lag, boost control and sequential ignition and injection. Big enterprises also started using another modern ECUs such as Bosch EDC15, Bosch ME9 series instead of DME Motronic 3.1, because of new emission standards and need to control such emission control systems as EGR (Exhaust Gas Recirculation), Swirl Flaps and others. The diagram below shows the wiring diagram for the standard ECU on the donor vehicle.

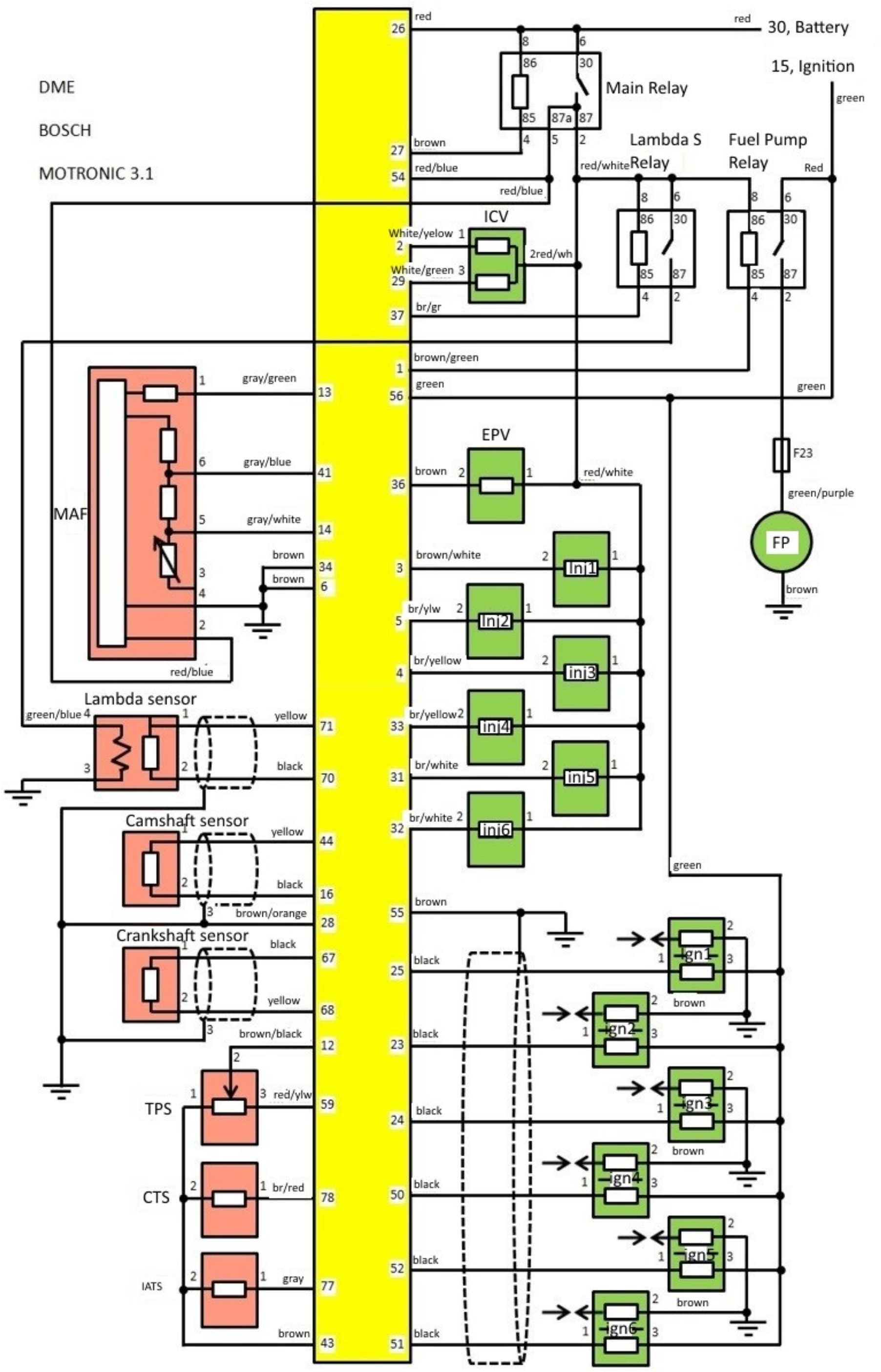


Figure 13. Factory ECU wiring diagram

Table 1. Shortage description table.

Shortage	Description
TPS	Throttle Position Sensor
MAF	Mass Air Flow Sensor
CTS	Coolant Temperature Sensor
IATS	Intake Air Temperature Sensor
FP	Fuel Pump
INJ	Injector
IGN	Ignition Coil
EVP	Evap Purge Valve
ICV	Idle Control Valve

Table 2. ECU connection diagram 1/2.

Pin	Description
1	GND Control of Fuel Pump Relay
2	GND Control of ICV closing
3	GND Control of Injector 1
4	GND Control of Injector 2
5	GND Control of Injector 3
6	GND
8	A/C
12	TPS signal wire
13	MAF heater
14	MAF signal wire
16	GND of Camshaft position sensor
17	N/U
23	GND Control of Iginition Coil 2
24	GND Control of Iginition Coil 3
25	GND Control of Iginition Coil 1
26	12V From the Battery
27	GND Control of Main Relay
28	GND (Braid wire of Camshaft sensor, Crankshaft sensor, Lambda sesor)
29	GND Control of ICV opening
31	GND Control of Injector 5
32	GND Control of Injector 6
33	GND Control of Injector 4
34	GND
36	GND Control of EPV
37	GND Control of Lambda Relay
41	MAF Signal + wire
43	Common Ground of TPS, CTS, IATS
44	plus signal of Camshaft Sensor
48	A/C
50	GND Control of Ignition Coil 4
51	GND Control of Ignition Coil 6
52	GND Control of Ignition Coil 5

Table 1. ECU connection diagram 2/2.

Pin	Description
54	12V from Main Relay
55	GND (Ignition Coils braid wires)
56	12V from Ignition terminal 15
59	12V TPS
60	?
65	AT
67	12V signal Crankshaft sensor
68	GND signal Crankshaft sensor
70	12V signal Lambda sensor
72	Dashboard speed signal
73	GND signal Lambda sensor
74	Engine RPM signal
77	12V IATS
78	12V CTS
81	N/U
85	A/C
86	A/C
87	RXD Diagnostic Plug
88	TXD Diagnostic Plug

1.3.4 Sensors (Inputs)

1.3.4.1. Crankshaft Sensor

Different kind of sensors are used in Automotive industry to detect the position of rotating objects, such as a crankshaft. In our case VR (Variable

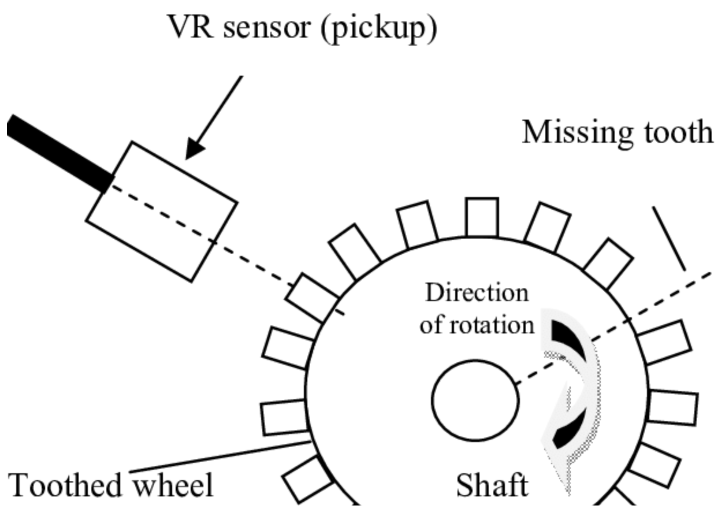


Figure 14. VR sensor and toothed wheel assembly diagram. Ihsan Omur Bucak (2010).

Reluctance) sensor is used. Operation principle of VR sensor is based on detecting the change in magnetic reluctance. Toothed ring is attached to the main crankshaft pulley and VR sensor is facing it. In particular case toothed wheel has a 60-2 configuration, which means there are 60 regular teethes and 2 in a raw are missing. As a toothed wheel rotates, a time-varying flux induces a proportional voltage in the coil inside the VR sensor, therefore this signal is processed by the control unit to determine the engine timing. That is the most important sensor in EFI system because according to its reading the ECU determines the timing of injection and ignition.

1.3.4.2. Coolant Temperature Sensor

Coolant temperature sensor is needed to continuously monitor the amount of heat the engine produces. Even though the cooling process of the engine is controlled by fully mechanical thermostat, some corrections to fuel mixture and ignition timing are sometimes made according to CTS readings. In performance-oriented vehicles automatic engine shutdown after reaching the desired maximum temperature point is widespread, to avoid the engine overheating. Operation principle is based on basic thermal resistor. ECU sends the voltage to the resistor and determines the resistance, processes the information and determines the coolant temperature.

1.3.4.3. Intake Air Temperature Sensor

There are different fuel mixture control algorithms. In described case the algorithm called Speed Density was used. It relies on “The Ideal Gas Law” to calculate the amount of air fed into the cylinder.

$$n = PV / RT$$

Where n is the number of moles of gas present.
MAP reading is used as P, $RPM * Displacement$ as V, R is a constant and T is the IAT reading. That is why IATS is needed in the EFI system.
Operation principle is just the same as CTS described above.

1.3.4.4. Throttle Position Sensor

TPS is based on basic rheostat, which changes the resistance according to Throttle position. After the data processing ECU gets a butterfly valve position in degrees. In some control algorithms like Alpha-N TPS signal is used to determine the engine load instead of MAP reading. But In my case TPS reading are going to be used just for some corrections and calibrations.

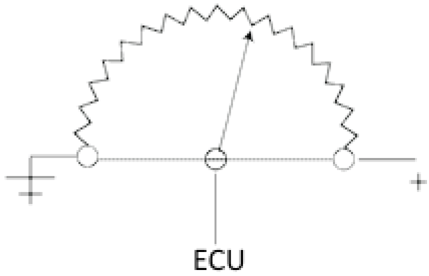


Figure 16. Throttle position sensor diagram.

1.3.4.5. Mass Air Flow Sensor

Mass air flow sensor is an outdated method of determining the amount of air coming to the cylinders due to its inaccuracy among forced induction applications. It was very popular in the very beginning of EFI system industry while most of the cars were naturally aspirated. The most common type of MAF sensor is so called “hot wire” sensor. Wire is placed inside of the air intake system, and constant voltage is applied to it. Wires gets heated while current is passing through and at the same time gets cooled down by the air flow. Its resistance changes because of temperature changed and therefore the current flowing through the wire is affected. ECU determines the amount of air according to current change inside the hot wire and IATS reading. In considered application, MAF was replaced by MAP which is described below.

1.3.4.6. Mass Air Pressure Sensor

As mentioned above in paragraph 2.3.4.3., MAP reading is needed. Operation principle and installation procedure are going to be described in that paragraph. In particular case, Megasquirt internal MAP sensor, which is soldered on the PCB is used. A vacuum line goes from ECU to the intake manifold to monitor the pressure. Operation principle of this sensor is based on basic diaphragm-based pressure transducer. Sensing element inside the sensor has a constant area and responds to the forced applied by air pressure. The force applied will deflect the diaphragm and this deflection is measured and converted into the digital signal.

1.3.4.7. Wideband Lambda Sensor

The most important sensor in terms of tuning, performance and engines safety is Wideband Lambda sensor. The lambda sensor application was already described in paragraph 2.1.3.2. It is needed to know the quality of fuel mixture. Wideband lambda is a performance part and is never installed onto civilian vehicles from the factory. Standard narrowband lambda sensor was upgraded with Innovate LC-1 Wideband sensor. As described in paragraph 2.1.3.2, AFR is a crucial parameter for the engine control. Narrowband sensor can only determine if the mixture is stoichiometric, lean or rich. While wideband sensor provides the accurate reading of the AFR. In my case from 8.0 up 20.0 AFR. That gives a possibility to tune the fuel tables to match the AFR reference tables precisely.

1.3.4.8. Clutch sensor

The clutch sensor is needed to determine whether the clutch pedal is depressed. It is needed for different racing features of the Megasquirt, such as Launch Control and Flat Shift. Operation principle is just same as any push-button. While the driver presses the pedal – in the very end it reaches the push-button.

1.3.5 Outputs

1.3.5.1. Fuel Injectors

This component and its operation principle was already described in paragraph 2.3.2.5.

1.3.5.2. Ignition Coils

Ignition coil is an induction coil which transforms a battery 12 Volt voltage into the thousands of volts (usually about 10 thousand) to create an electric spark in the spark plug. In described case 6 independent ignition coils were used, while some other cars might have single coil for every cylinder or any other configuration.

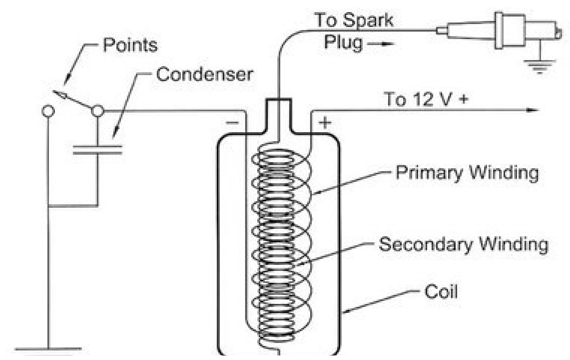


Figure 17. Ignition coil diagram. What-When-How (2018).

1.3.5.3. Ignition Coil Drivers and Schematic

Ignition spark timing is a crucial parameter as mentioned above, and a strong current flowing through the ignition coil and a very precise control at the same time is needed. There are 6 separate coils in the ignition system and therefore to obtain a sequential ignition it is necessary to have 6 separate coil drivers which will control the current. Megasquirt cannot provide the current enough for the coil to create a spark, so a specific ignition driver produced especially for automotive industry was used. BIP373 ignition coil drivers are produced by Bosch and suit perfectly for the application. Connection diagram is shown below. Donor engine is equipped with the 6-cylinder engine, so to obtain a semi-sequential ignition is needed to fire two ignition coils at once, so it is enough to use only 3 outputs from the Megasquirt and use one output for two drivers. Connection will be covered in detail in paragraph 3.

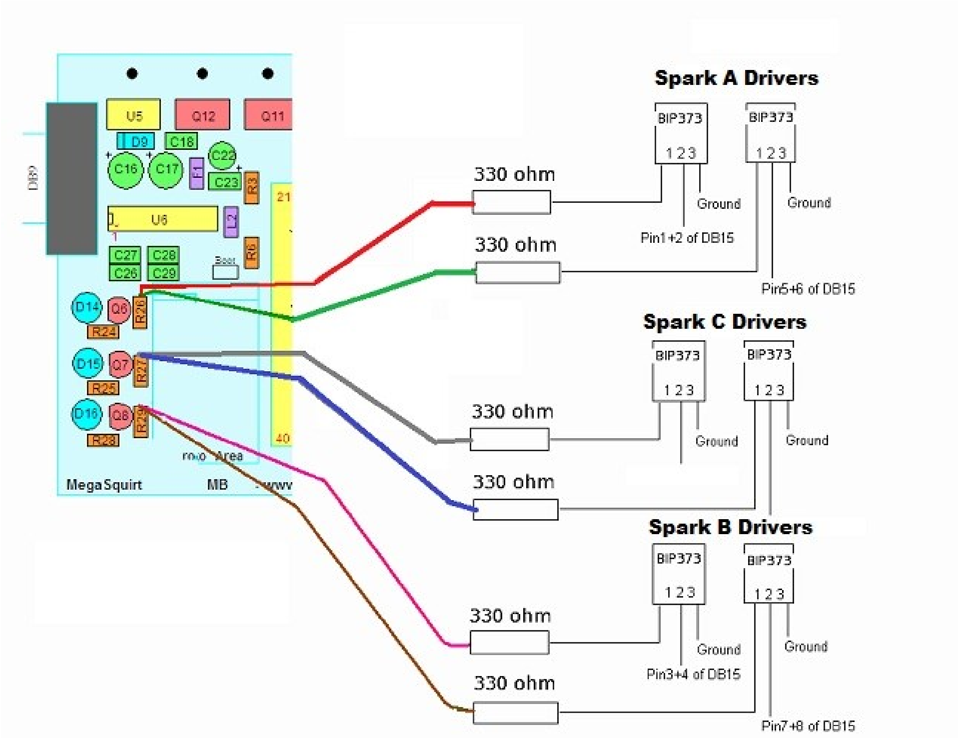


Figure 18. Ignition coil driver connection diagram. MSextra (2007).

1.3.5.4. Idle control valve

Idle control valve is used to control the engine at idle operation (while the throttle body is fully closed). It is a bypass valve, which lets the air to bypass the closed throttle body and to get into the intake manifold. This unit contains a linear servo actuator that controls a plunger, allowing a certain amount of air to bypass the throttle body. Unit is controlled by the ECU and its control will be covered in detail in paragraph 4.

2 MEGASQUIRT ASSEMBLY

Megasquirt is an opensource aftermarket ECU, designed by Bruce Bowling and Al Grippo in 2001 to control a wide range of different non-diesel engines. Controller features all the basic ECU functions such as ignition timing control, injection control, but in a more advanced way then the civilian ECUs and adds some additional features. The project is open source, which means the source code could be downloaded and modified by the end-user, even though PCB design of the Megasquirt daughtercard (small PCB containing main processor) is a subject to patents. Megasquirt is distributed in different ways, it is possible to purchase a ready unit and PCB separately. A daughter card, MS-2 V3.0 PCB and all the components were bought separately, to build the unit and the process is being described in that paragraph. (Megasquirt, 2005)

2.1 Components

The list of all the components needed to assemble V3.0 PCB is presented below.

Table 4. Components list. Megamanual (2010).

QTY Needed	*QTY Ordered*	*MegaSquirt References*	*Digi-Key Part Num.*	*Unit Cost*	*Circuit*	*Component Name*
10	10	C1,C3,C13,C18,C19, C23,C26,C27, C28, C29	399-4329-ND	0.15	Basic Components	Capacitor 0.1µF 50V 10% CER RADIAL - X7R
3	3	C11,C21,C32	399-4326-ND	0.32	Basic Components	Capacitor 0.01µF 50V 10% CER RADIAL
2	2	C16,C17	399-1420-ND or 399-3584-ND	3.75	Basic Components	Capacitor TANT 22µF 25V 10% RAD
4	5	C2,C9, C10, C30	399-4353-ND	0.36	Basic Components	Capacitor 0.22µF 50V 10% CER RADIAL - X7R
1	1	C20	399-4361-ND	0.35	Basic Components	Capacitor 0.033µF 50V 10% CER RADIAL
2	2	C14,C22	399-3559-ND	1.46	Basic Components	Capacitor TANT 4.7µF

						25V 10% RAD
1	1	C24	399-4239-ND	0.43	Basic Components	Capacitor 47PF 200V 5% CER RADIAL
1	1	C25	399-4344-ND	0.44	Basic Components	Capacitor 22PF 200V 5% CER RADIAL
6	10	C4,C6,C8,C12, C15,C31	399-4202-ND	0.218	Basic Components	Capacitor 0.001µF 100V 10% CER RADIAL - X7R
2	2	C5,C7	399-4389-ND	0.47	Basic Components	Capacitor 1.0µF 50V 10% CER RADIAL - X7R
7	10	D1-3,D9-11,D24	1N4001DICT-ND	0.137	Basic Components	Diode GPP 50V 1A DO-41
1	1	D12	1727-4231-1-ND	0.3	Basic Components	Diode Zener 24V 1W 5% DO-41
1	1	D13	1N4742AFS-ND	0.22	Basic Components	Diode Zener 12V 1W 5% DO-41
3	10	D14,D15,D16	67-1102-ND	0.2888	Basic Components	LED Red Translucent Round
2	2	D17,D18	1N5819DICT-ND	0.39	Basic Components	Diode Schottky 40V 1A DO-41
1	1	D19	1N4734AFSCT-ND	0.23	Basic Components	Diode Zener 5.6V 1W 5% DO-41
2	2	D4,D8	1N4748A-ND	0.22	Basic Components	Diode Zener 22V 1W 5% DO-41
2	2	D5,D7	UF5401-E3/54GICT	0.64	Active flyback	Diode FAST REC 100V 3A DO-201AD

3	3	D6,D20,D21	1N4753A_T50 ACT-ND	0.23	Basic Components	Diode Zener 36V 1W 5% DO-41
2	2	F1, F2	RXEF050HF-ND	0.39	Spares	Polyswitch RXE Series 0.50A HOLD
2	2	L1,L2	495-5611-1-ND	0.78	Basic Components	Choke RF Varnished 1UH 20%
1	1	MOV1	P7315-ND	1.62	Basic Components	Surge absorber 20MM 22V 2000A ZNR
1	1	P1	A23305-ND/A32119-ND	5.07/2.47	Basic Components	Connector D-SUB RECPT R/A 9POS PCB AU
1	1	P2	A23289-ND or A32103-ND	7.3/6.86	Basic Components	Connector D-SUB PLUG R/A 37POS PCB AU
2	2	Q1,Q5	IRFIZ34GPBF-ND	2.21	Spares	HEX/MOSFET N-CH 60V 20A TO-220FP
1	1	Q16	FGP3040G2_F085-ND	2.17	High-Current Ignition Driver	IC DRIVER 340V 7.5A ISOWATT 220
2	2	Q2,Q4	ZTX450-ND	0.67	Basic Components	Transistor NPN 45V 1000MA TO-92
2	2	Q22,Q23	ZTX553-ND	0.66	VR Sensor	Transistor PNP 100V 1000MA TO-92
2	2	Q3,Q11	TIP42CGOS-ND	0.6	Basic Components	Transistor PNP 6A 100V HI PWR TO220AB
9	9	Q6,Q7,Q8,Q10, Q13, Q14,Q15,Q19, Q20	2N3904FS-ND	0.174	Basic Components	Transistor NPN SS GP 200MA TO-92
2	2	Q9,Q12	TIP125TU-ND	0.62	Active flyback	Transistor PNP DARL -100V -

						5A TO-220
7	10	R16,R19,R26,R27, R29,R42,R55	1.0KEBK-ND	0.077	Basic Components	Resistor 1.0K Ohm 1/8W 5% Carbon Film
5	5	R2,R9,R10,R32,R36	1.0KQBK-ND	0.1	Basic Components	Resistor 1.0K Ohm ¼W 5% Carbon Film
9	10	R1,R6,R14,R17,R21, R44,R48,R53,R54	10KEBK-ND	0.077	Basic Components	Resistor 10K Ohm 1/8W 5% Carbon Film
3	5	R22,R49,R50	100KEBK-ND	0.1	Basic Components	Resistor 100K Ohm 1/8W 5% Carbon Film
2	5	R11,R51	1.0MEBK-ND	0.1	Basic Components	Resistor 1.0M Ohm 1/8W 5% Carbon Film
1	5	R23	10MEBK-ND	0.1	Basic Components	Resistor 10M Ohm 1/8W 5% Carbon Film
2	5	R15,R20	22QBK-ND	0.1	Basic Components	Resistor 22 Ohm ¼W 5% Carbon Film
2	5	R4,R7	2.49KXBK-ND	0.1	Basic Components	Resistor 2.49K Ohm ¼W 1% Metal Film
6	10	R18,R30,R31,R33, R34,R35	270QBK-ND	0.06	Basic Components	Resistor 270 Ohm ¼W 5% Carbon Film
3	5	R24,R25,R28	330QBK-ND	0.1	Basic Components	Resistor 330 Ohm ¼W 5% Carbon Film
1	5	R12	390H-ND	0.1	Basic Components	Resistor 390 Ohm ½W 5% Carbon Film

1	5	R13	4.7KEBK-ND	0.1	Hall/Coil(-Sensor	Resistor 4.7K Ohm 1/8W 5% Carbon Film
1	5	R3	51KEBK-ND	0.1	Basic Components	Resistor 51K Ohm 1/8W 5% Carbon Film
2	2	R37,R38	TAH20PR050JE-ND	9.62	Current Limiting	Resistor .05 Ohm 20W TO220
2	5	R39,R40	1.0H-ND	0.1	Basic Components	Resistor 1.0 Ohm ½W 5% Carbon Film
1	1	R43	13FR010E-ND	2.76	High-Current Ignition Driver	Resistor Current Sense .010 Ohm 3W
2	5	R45, R46	10KQBK-ND	0.1	Basic Components	Resistor 10K Ohm ¼W 5% Carbon Film
2	5	R47, R57	47KEBK-ND	0.1	Basic Components	Resistor 47K Ohm 1/8W 5% Carbon Film
2	5	R5,R8	2.2KQBK-ND	0.1	Basic Components	Resistor 2.2K Ohm ¼W 5% Carbon Film
1	1	R52	CT94EW104-ND	1.56	VR Sensor	Trim Pot 100K Ohm TOP ADJ
1	1	R56	CT94EW103-ND	1.56	VR Sensor	Trim Pot 10K Ohm TOP ADJ
1	1	U3	160-1300-5-ND	0.48	Hall/Coil(-Sensor	Optoisolator w/base 6-DIP
1	1	U4	CLA360-ND	1.89	Basic Components	MOSFET Driver LS 4A DUAL 8DIP
1	1	U5	LM2937ET-5.0-ND	1.83	Spares	Regulator LDO TO-220
1	1	U6	MAX232AEPE+-ND or	6.31/4.65	Basic Components	DVR/RCVR 5V

			LT1181ACN#PBF-ND			RS232 16 DIP
1	1	U7	LM2904NFS-ND	0.50	VR Sensor	OpAmp Dual SGL SUPP HS 8DIP
1	1	Y1	300-1002-ND	0.42	Spares	Crystal 32.768KHz CYL 12.5PF
1	2	NA	36-4724-ND	2.13	Active flyback	Mounting Hardware TO-220
1	1	NA	AE10018-ND	2.12	Basic Components	Socket Machine Pin ST 40POS GOLD
1	1	NA	AE10013-ND	0.91	Sockets	Socket Machine Pin ST 16POS GOLD (Max232)
2	2	NA	AE10011-ND	0.50	Sockets	Socket Machine Pin ST 8POS GOLD (IXDI404PI)
1	1	NA	AE10021-ND	0.73	Sockets	Socket Machine Pin ST 6POS GOLD (4N25)
3	5	NA	516-1394-ND	0.61	Basic Components	Bezel LED Panel 5MM BK Nylon 2PC
1	1	NA	237FER-ND	2.5	Cables	Connector DB-37 Female;
1	1	NA	937GME-ND	2.58	Cables	DB-37 Hood;
1	1	NA	AE1020-ND	3.74	Cables	DB-9 Straight-through cable (6.5 feet/2 meters)

List of all the components is available at official Megasquirt website. All of the components mentioned in the table above were bought at Digi-Key to proceed with building process. Custom PCB was ordered from Chinese manufacturer and made according to official Megasquirt drawing. Daughtercard was purchased straight from official megasquirt store. Picture of all the components is presented below.

Figure 19. Components

2.2 V3.0 PCB Schematic

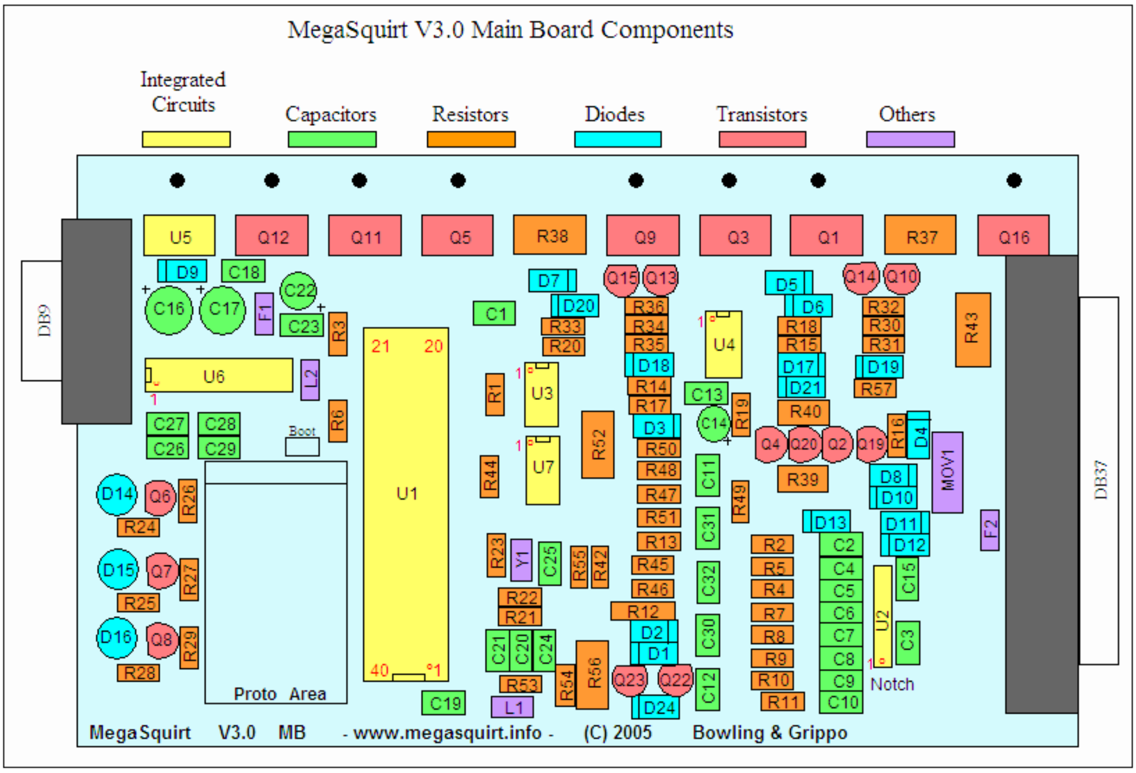


Figure 20. Megasquirt mainboard assembly. Megamanual (2010).

2.3 Soldering

Soldering the Megasquirt main board takes about 6 hours. All the diagrams are found from the official website. There are 3 different testing procedures during the process, to make troubleshooting easier. All the testing procedures have been passed successfully which means a functioning Megasquirt mainboard have been built correctly. Picture of the assembled unit is presented below.

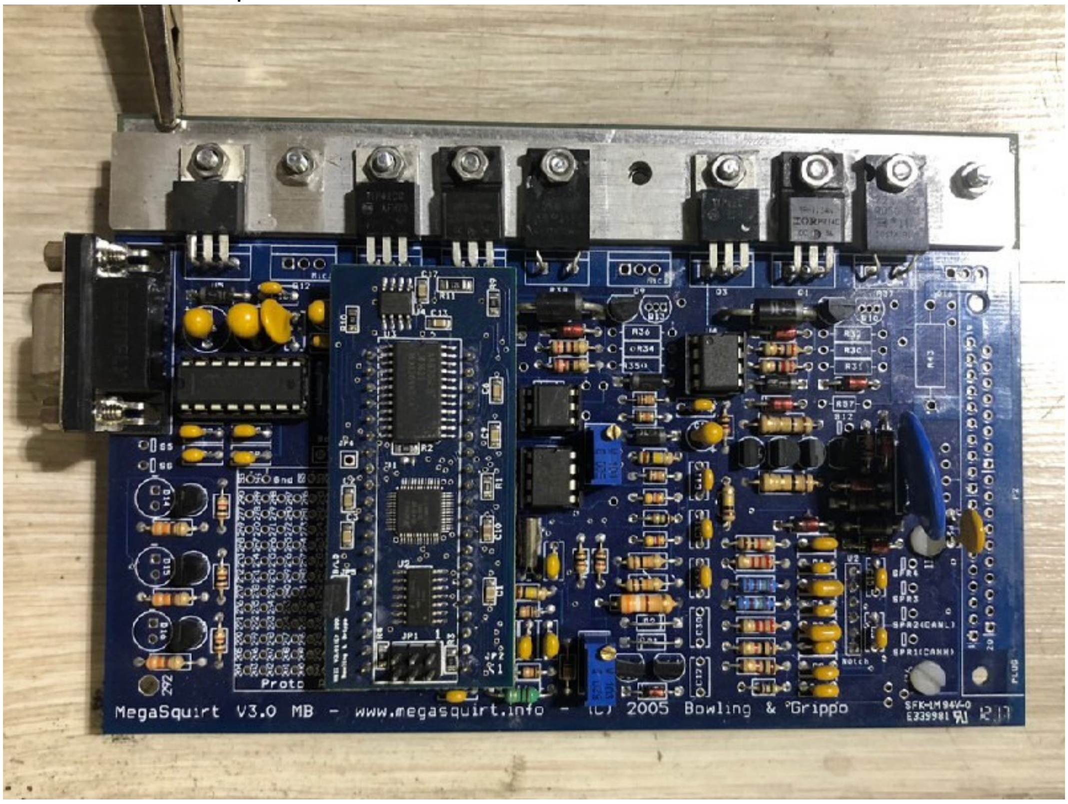


Figure 21. Assembled unit

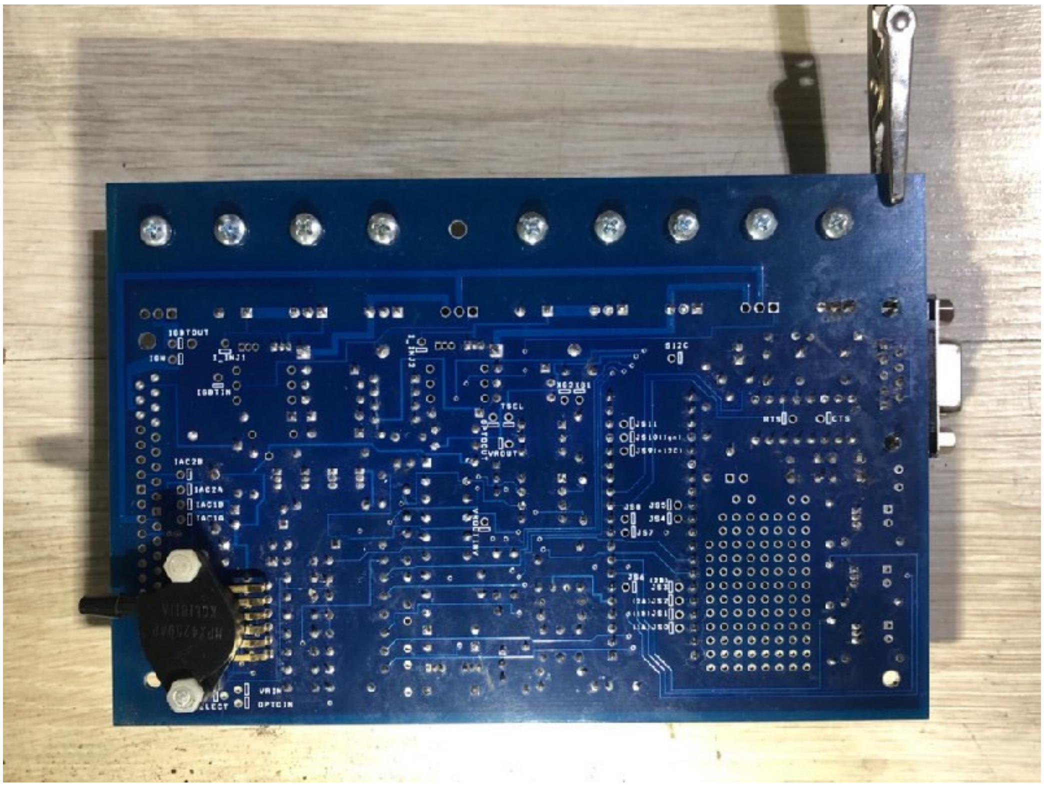


Figure 22. Assembled unit

2.4 Inputs and Outputs

Wiring diagram provided by Megasquirt is presented below. Connection in researched case has 2 main differences. Wideband lambda with integrated controller is used instead of narrowband lambda shown on the diagram. Separate ignition drivers instead of single ignition signal are used to control semi-sequential ignition circuit.

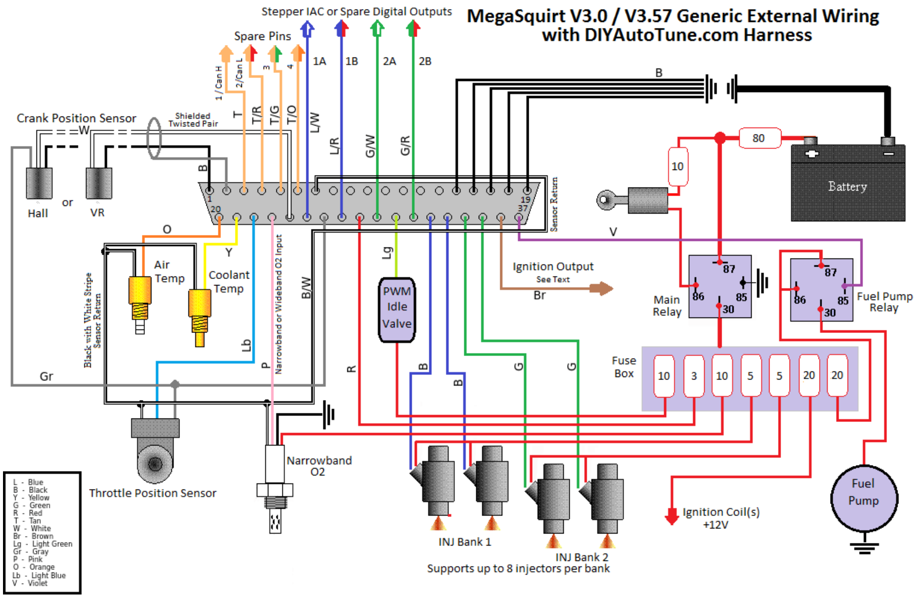


Figure 23. Megasquirt wiring diagram. Megamanual (2010).

2.5 Casing

A custom casing for the PCB and ignition coil drivers was designed. It was made from 1mm duralumin using the CNC cutter. The 3D design was made using the SolidWorks software. Box features slide-in rails for the Megasquirt PCB and mounting brackets for the ignition coil drivers heatsink on top of that.

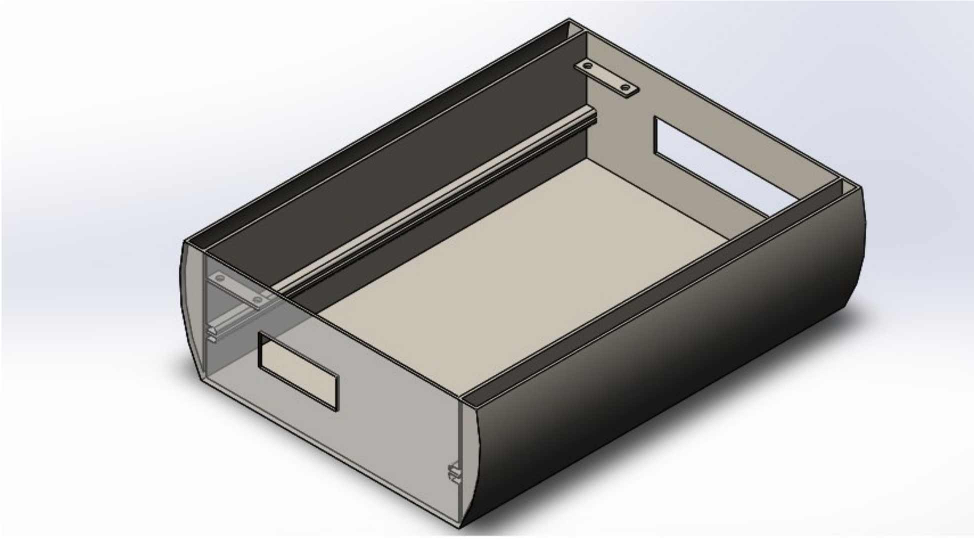


Figure 24. Casing 3D model

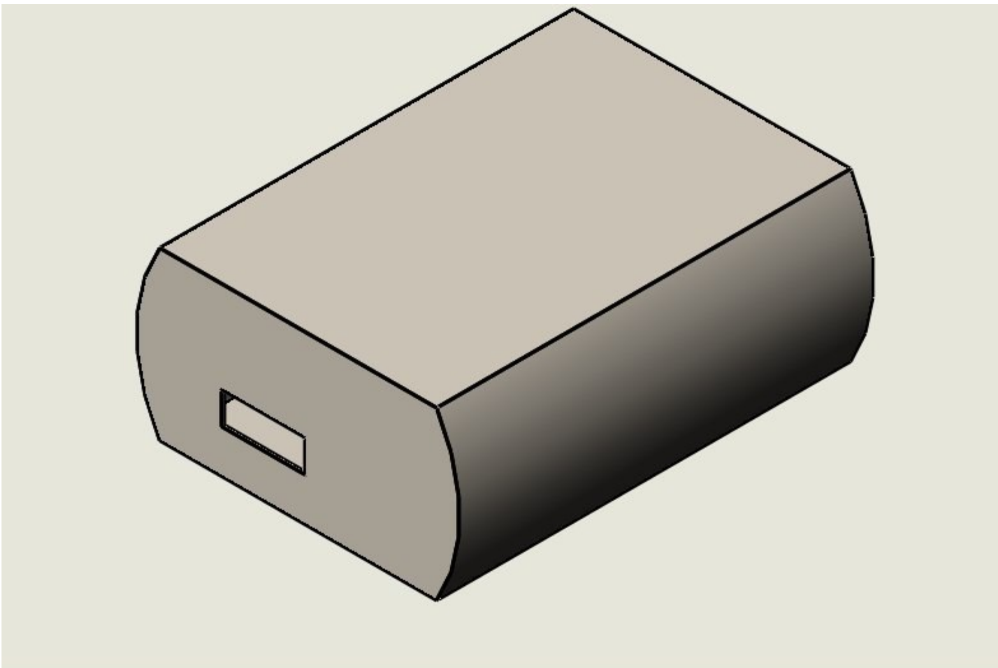


Figure 23. Casing 3D model

2.6 Schematic of Ignition Modules

For the ignition drivers, covered in paragraph 2.3.5.3 an additional heatsink was added to the casing, because ignition drivers produce a lot of heat and might overheat easily without the proper cooling. Even though BIP373 has a thermal protection (shut off after reaching a 195°C threshold) and it is not possible to burn them, it is important to have a stable spark and it is absolutely necessary to ensure that drivers will never reach the shut off threshold, because it might lead to detonation and therefore severe engine damage. Ignition drivers will be mounted onto the heatsink using the mica insulator, because the mounting tab of the driver has a different potential then a ground and.

3 WIRING AND INSTALLATION

3.1 Wiring Harness

To simplify the process of wiring the standard wiring harness of Bosch DME Motronic 3.1 was used, the schematic is presented in paragraph 2.3.3. Schematic of Megasquirt inputs and outputs is presented in paragraph 3.4. Connections table presented below was created according to the two diagrams mentioned above. Based on this table the wires from Motronic 3.1 88pin socket was connected to DB37 Female connector, which was connected to the Megasquirt directly.

Table 5. I/O table.

Megasquirt Pin	Motronic Pin	Function MS	Function Motronic
1	67	VR sensor GND	Crank sensor
2		VR sensor shield	
3		Spare1	
4	74	Spare2	Tach signal from JS0 (IAC1A)
5	44	Spare3	Camshaft sensor GND
6	16	Spare4	Camshaft sensor GND
7	71	Sensor GND	Lambda sensor GND
8	55	spare GND	GND
9	34	spare GND	GND
10		spare GND	
11		spare GND	
12		spare GND	
13		spare GND	
14		spare GND	
15	28	POWER GND	
16	28	POWER GND	
17	6	POWER GND	
18	6	POWER GND	
19	43	POWER GND	Sensors GND
20	77	IAT sensor input	
21	78	CT sensor input	
22	12	TP sensor input	
23	70	Lambda sensor input	
24	68	VR Signal	
25		IAC1A	

26		59	5V TPS+	
27			IAC1B (D)	
28		54	12V in	ECU Main relay
29	BIP337		IAC2A (C)	
30		29	FIDLE	ICV
31	BIP337		IAC2B (B)	
32	3,4,5		inj1	Injector bank 1 (1,2,3)
33	3,4,5		inj1	Injector bank 1 (1,2,3)
34	31,32,33		inj2	Injector bank 2 (4,5,6)
35	31,32,34		inj2	Injector bank 2 (4,5,6)
36	BIP337		IGN (A)	
37		1,37	Fuel Pump	Fuel Pump and Lambda relays

3.2 **Installation of Wideband Lambda Sensor**

To obtain the proper readings from the Wideband Lambda sensor it is needed to mount the sensor in a proper place around the exhaust pipe. According to Innovate Motorsport instructions, it is necessary to install the lambda sensor 24 inches downstream from the turbocharger exhaust outlet. If the sensor will be mounted too close to the exhaust outlet it will be affected by extremely high temperatures, whereas if it is mounted too far away it is going to provide wrong readings. (Innovate Motorsport, 2012)

4 **TUNING**

In that paragraph the basic settings needed to start up the engine are going to be described and in the last section of the paragraph it will be followed with description of the process of fine-tuning the engine to the optimal performance using the dynamometric stand.

4.1 **Tuning Software for MS**

Software, used to tune the Megasquirt controller is called TunerStudio MS, and it is released by the company called EFI Analytics. Software is free and allows to use all the basic features in free mode. It is possible to buy a licensed version and unlock the access to such features as VE-table automatic tune according to AFR-wish table.

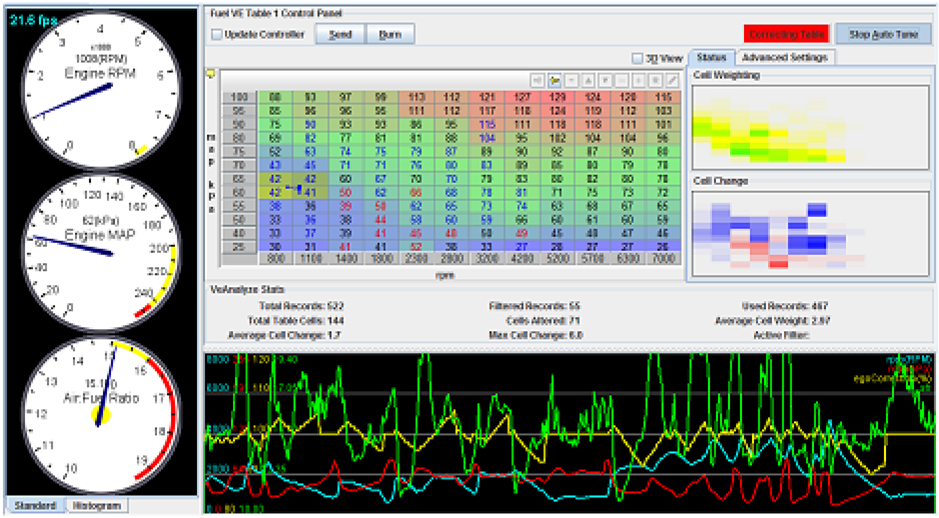


Figure 25. TunerStudioMS interface sample. TunerStudioMS (2013).

4.2 Basic Settings

To start the engine, it is needed to make sure that the two main parameters are set properly. First of all, as mentioned above, the most crucial parameter is the crankshaft position signal, provided from the VR sensor and trigger wheel. Second most important parameter is the injector criteria, which will set the main injector parameters needed to calculate the amount of fuel, controlled by the VE and Enrichments tables.

4.2.1 Trigger Wheel Settings

To enter the right parameters in Basic Ignition Settings, it is necessary to know the specifications of toothed wheel. Three main parameters matter the most: 1) Number of teethes, 2) number of missing teethes, 3) angle of tooth #1. Using a protractor, I have measured the first tooth and obtained the last unknown parameter. Results are presented on the screenshot below. All the standard parameters were used, other than the 3 mentioned above.

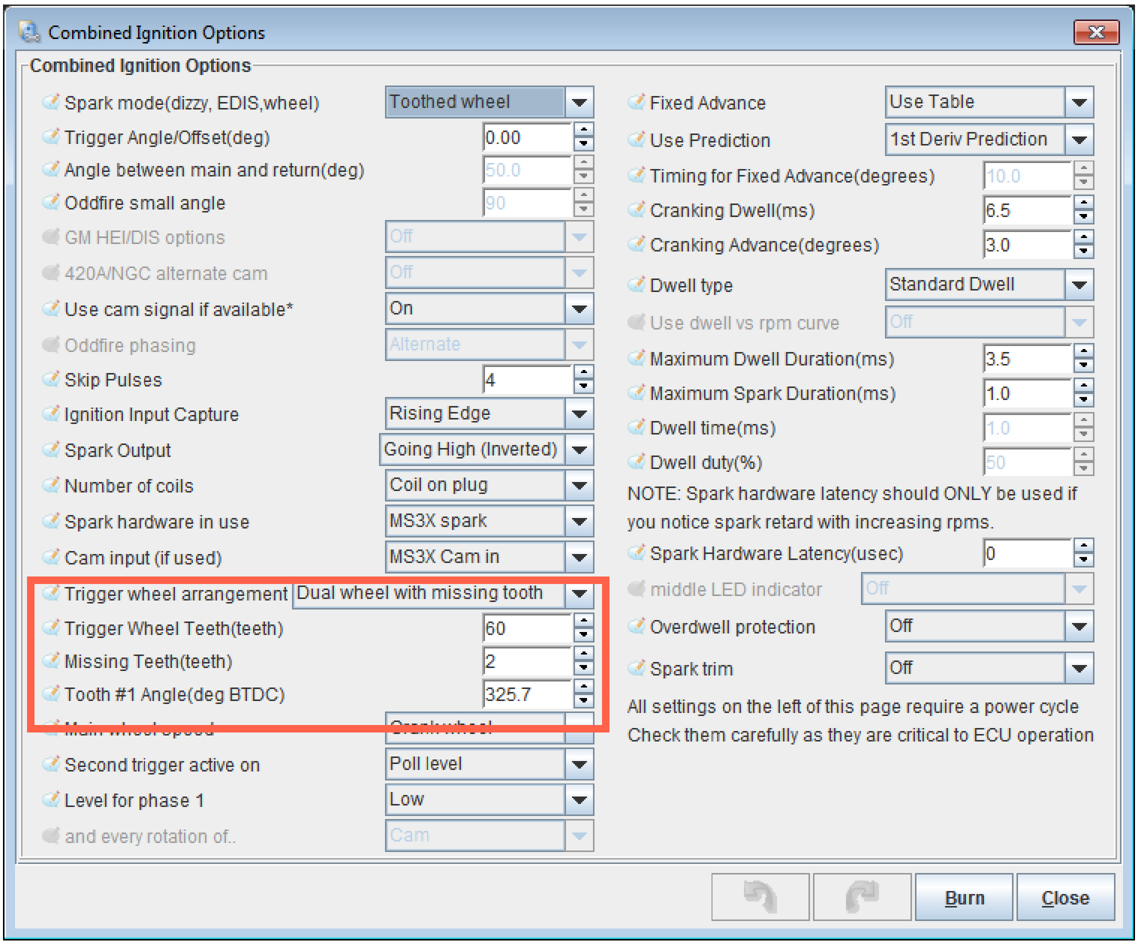


Figure 26. Ignition settings TunerStudioMS.

4.2.2 Injector criteria

To start the engine, it is necessary to explain the controller which kind of injectors are used in the application to get the right amount of fuel flowing. There is an integrated calculator inside the TunerStudioMS software, which calculates the Required Fuel parameter depending on Injector Opening Time, Battery Voltage Correction, PWM Time Threshold, Injector PWM Period, Engine Displacement, Number of cylinders, Injector flow, and stoichiometric AFR for the specific fuel use. After entering all the needed values to the calculator, it returned 5.7 as a Required Fuel Value. After that basic engine configurations were chosen, such as stroke, number of cylinders and firing order.

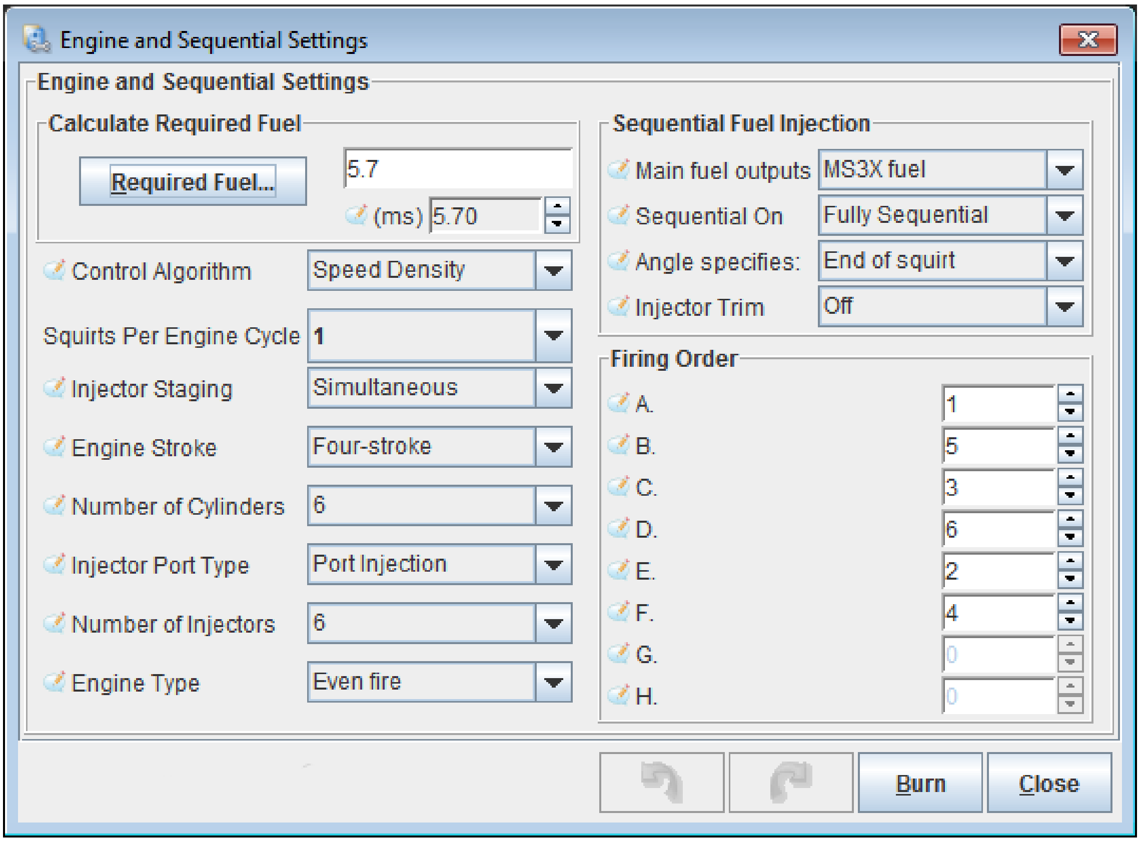


Figure 27. Fueling settings TunerStudioMS

4.3 **Ignition Settings**

After all the basics settings are done it is necessary to create the base ignition advance table.

4.3.1 Ignition Advance Table

That is the table, which controller is going to use to determine the spark timing according to crankshaft sensor readings. It is very important during the base-tune to make the table as safe as possible in order to avoid detonation inside the cylinders. Therefore, in paragraph 5.5 the process of further ignition performance tuning is going to be covered. Megasquirt provide a basic instruction to determine the maximum advance angle according to engine parameters. Instructions are presented below.

Making a Spark Advance Table

You can get a base starting point for the VE table by using the 'Tables/VE Table/Tools/VE Specific/Generate Table' function of MegaTune, using the peak horsepower and torque figures for your engine.

For timing, we don't have a generator written yet. The basic principles are to determine a maximum advance for your engine and work backwards from there with heuristics ('*rules of thumb*'):

- older engines (1960s up to 1990 or so) with two valves - max advance = 36°
- newer two-valve engines - max advance = 30°
- three or four valve engines - max advance = 26°

then adjust for bore size:

- under 3.5" (89mm) - subtract 3°
- between 3.5" and 4.000" (101.6mm) - no adjustment
- over 4.001" (+101.6mm) - add 3°

then adjust for the fuel:

- regular - subtract 2°
- mid-grade - subtract 1°
- premium - no adjustment

That gives us a maximum advance figure. It you have an aftermarket combination with a good squish area and optimized quench, subtract another 2°. If you have a flathead, add 3° or 4° or more.

We will use this to fill in the table at 100 kPa from 3000 rpm to the redline.

From idle to 3000 rpm, we want the advance (@100kPa) to increase fairly linearly from the idle advance to the maximum advance. idle advance is really a matter of tuning, but assume 8° to 16° in most cases, with stock engines being on the lower end, and 'hotter' engines being on the upper end.

So if we have a hot engine with 36° maximum advance and 16° idle advance (at 800rpm), the spark table might look like this for 100kPa:

```
100    16°  16°   18°   24°   28°   36°

rpm    600  800  1000  1500  2000  3000
```

Below 100 kPa, we add 0.3° per 1 kPa drop. So for example, if our total spark at 100kPa and 4000 rpm was 36°, the advance at 50 kPa would be:
36° + 0.3° x (100-50) = 51°

and the advance at 45 kPa and 800 rpm would be:

16° + 0.3° x (100-45) = 32.5°

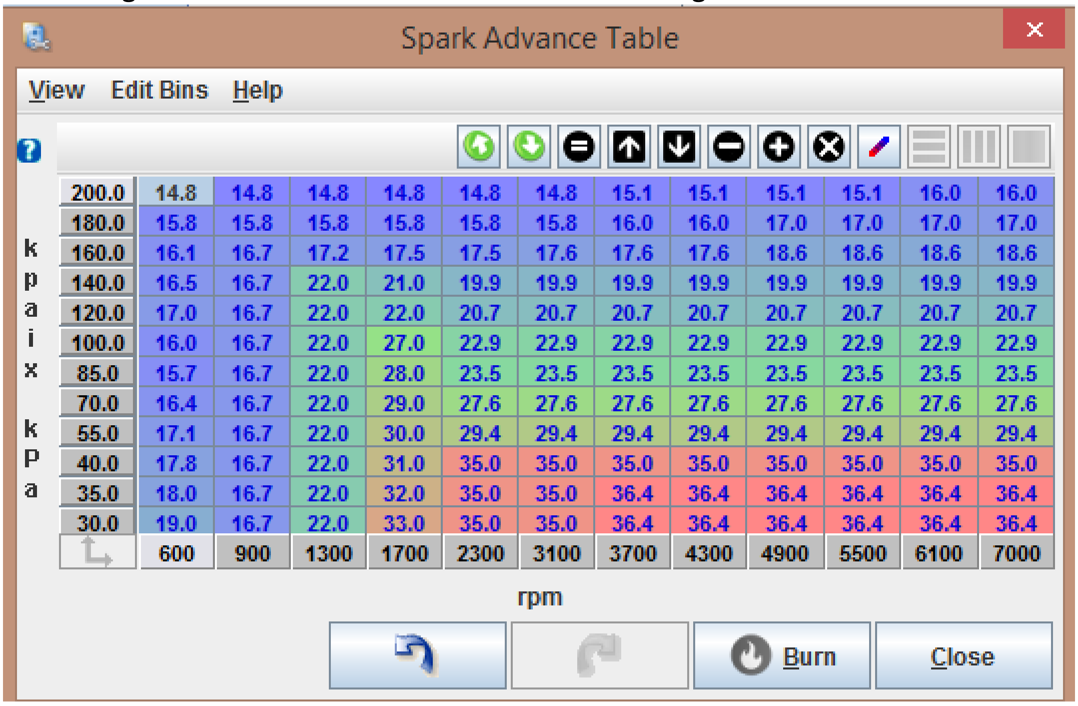
However all of these would need to be tuned, and it often helps idle stability to limit the advance at idle to under 20°.

Finally, for boosted engines, you subtract 0.3° of advance for every kPa above 100 (it's not a coincidence that this is the same factor as for the 'vacuum' adjustments). Because 101.3kPa=~14.7psi, this works out to ~2° per pound of boost. It is often the case that you want to limit the retard under boost as well, typically so that it takes out no more than about Â½ of the maximum advance at 100 kPa.

None of these will give you the 'right' values for your engine though, and like the VE table calculator, are just a relatively safe starting point. They should be somewhat closer than starting with an empty table, though! [18]

Figure 27. Casing 3D model. Ignition Advance table creation manual. Megamanual (2010).

According to this instruction above a table for the engine was created.



kpaix kpa	600	900	1300	1700	2300	3100	3700	4300	4900	5500	6100	7000
200.0	14.8	14.8	14.8	14.8	14.8	14.8	15.1	15.1	15.1	15.1	16.0	16.0
180.0	15.8	15.8	15.8	15.8	15.8	15.8	16.0	16.0	17.0	17.0	17.0	17.0
160.0	16.1	16.7	17.2	17.5	17.5	17.6	17.6	17.6	18.6	18.6	18.6	18.6
140.0	16.5	16.7	22.0	21.0	19.9	19.9	19.9	19.9	19.9	19.9	19.9	19.9
120.0	17.0	16.7	22.0	22.0	20.7	20.7	20.7	20.7	20.7	20.7	20.7	20.7
100.0	16.0	16.7	22.0	27.0	22.9	22.9	22.9	22.9	22.9	22.9	22.9	22.9
85.0	15.7	16.7	22.0	28.0	23.5	23.5	23.5	23.5	23.5	23.5	23.5	23.5
70.0	16.4	16.7	22.0	29.0	27.6	27.6	27.6	27.6	27.6	27.6	27.6	27.6
55.0	17.1	16.7	22.0	30.0	29.4	29.4	29.4	29.4	29.4	29.4	29.4	29.4
40.0	17.8	16.7	22.0	31.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0
35.0	18.0	16.7	22.0	32.0	35.0	35.0	36.4	36.4	36.4	36.4	36.4	36.4
30.0	19.0	16.7	22.0	33.0	35.0	35.0	36.4	36.4	36.4	36.4	36.4	36.4

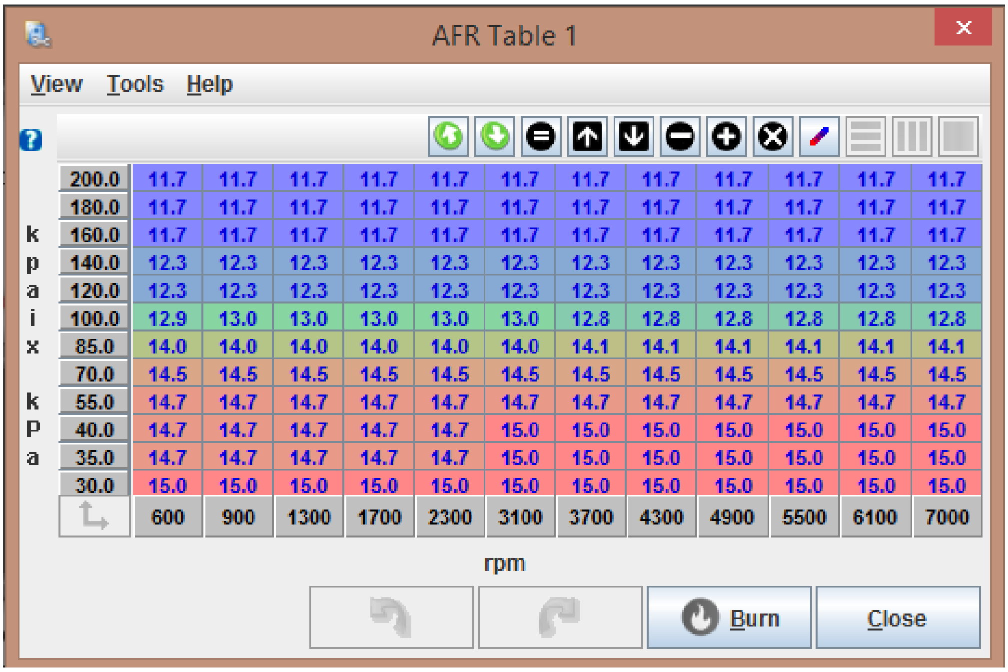
Figure 28. Spark advance table

4.4 Fuel Settings

In that paragraph main fuelling maps are covered. First of all, the AFR reference table is configured, followed by main VE table and Enrichments settings.

4.4.1 AFR Table

AFR Table is mostly the reference table, it is not going to be used as a control table for the controller in considered application, the AFR-correction feature is not going to be used. But it is going to be used during the automatic VE-table correction procedure, that is the main reason to create it. Making AFR table is very easy process if user understands the basic tuning theory. The main goal is maintaining the engine to operate on stoichiometric (14.7 for gasoline) mixture, unless it needs rich mixture while operating in WOT (Wide Open Throttle) range. According to my own basic knowledge of tuning theory I have created the table presented below.



AFR Table 1

View Tools Help

kpaix kPa	600	900	1300	1700	2300	3100	3700	4300	4900	5500	6100	7000
200.0	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7
180.0	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7
160.0	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7
140.0	12.3	12.3	12.3	12.3	12.3	12.3	12.3	12.3	12.3	12.3	12.3	12.3
120.0	12.3	12.3	12.3	12.3	12.3	12.3	12.3	12.3	12.3	12.3	12.3	12.3
100.0	12.9	13.0	13.0	13.0	13.0	13.0	12.8	12.8	12.8	12.8	12.8	12.8
85.0	14.0	14.0	14.0	14.0	14.0	14.0	14.1	14.1	14.1	14.1	14.1	14.1
70.0	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5
55.0	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7
40.0	14.7	14.7	14.7	14.7	14.7	15.0	15.0	15.0	15.0	15.0	15.0	15.0
35.0	14.7	14.7	14.7	14.7	14.7	15.0	15.0	15.0	15.0	15.0	15.0	15.0
30.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0

rpm

Burn Close

Figure 29. AFR table

From the table above it is clear that ECU is running the engine on stoichiometric mixture unless the pressure in the intake manifold gets over 85 kPa. At WOT before boost (<101 kPa) engine runs on a rich mixture and mixture starts to enrich even further with the raising pressure in the intake manifold up to 11.7 which is considered a safe quality of mixture for the boost pressure of 1 bar.

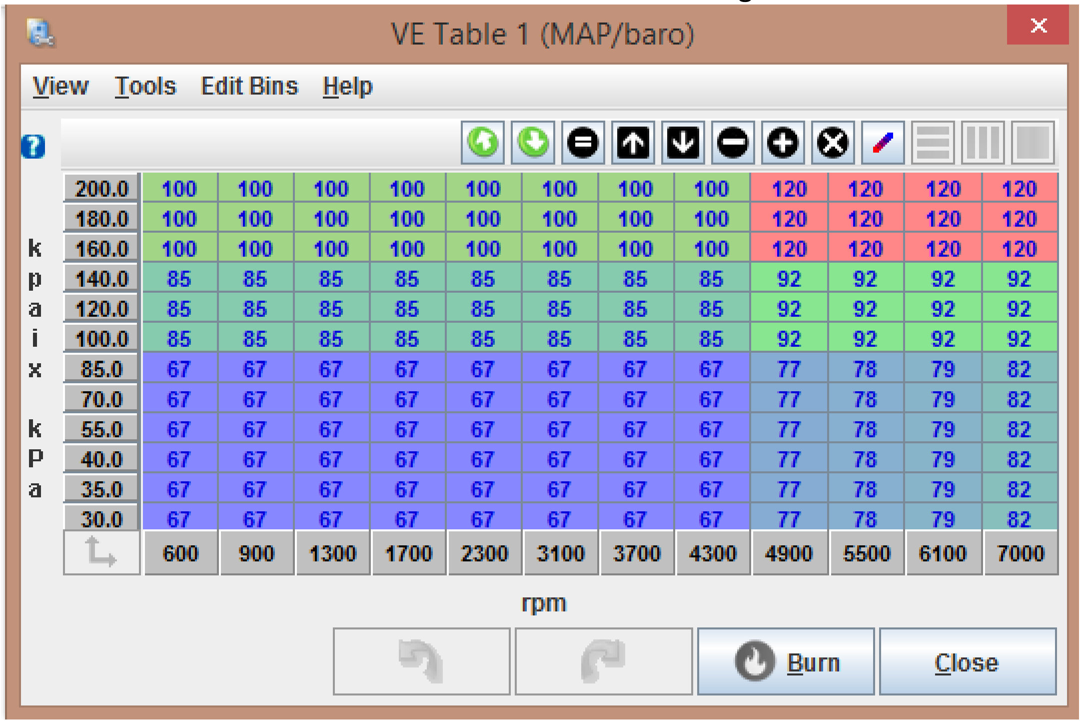
4.4.2 VE Table

VE (Volumetric Efficiency) Table is the main fueling table, which determines the amount of fuel flown by the injectors into the intake manifold ports. The best way to create a starting point table is to use a special calculator available online. Sample of the calculator is presented below.

Idle RPM:	800 RPM	300 rpm minimum
RPM redline (maximum operating rpm):	7500 RPM	12000 rpm maximum
Peak flywheel horsepower:	390 HP @	6500 RPM
Peak torque:	400 lbÂ·ft @	3200 RPM
Engine displacement:	2 liters	
Engine maximum boost level: (0 for naturally aspirated, max. boost (psi) for turbo/supercharged)	3 psi	21 psi maximum
AFR table dimensions:	12×12 ▼	• MS-I uses 8×8 tables; • MS-II, MicroSquirt, and the Sequencer user 12×12 tables.

Figure 30. VE table calculator. Megamanual (2010).

Table which was calculated with the input above is presented below. This table is good starting point to start the engine up and start calibrating it using the automatic tune feature, which will adjust the table according to AFR reference table and wideband lambda sensor readings.



kPa \ rpm	600	900	1300	1700	2300	3100	3700	4300	4900	5500	6100	7000
200.0	100	100	100	100	100	100	100	100	120	120	120	120
180.0	100	100	100	100	100	100	100	100	120	120	120	120
160.0	100	100	100	100	100	100	100	100	120	120	120	120
140.0	85	85	85	85	85	85	85	85	92	92	92	92
120.0	85	85	85	85	85	85	85	85	92	92	92	92
100.0	85	85	85	85	85	85	85	85	92	92	92	92
85.0	67	67	67	67	67	67	67	67	77	78	79	82
70.0	67	67	67	67	67	67	67	67	77	78	79	82
55.0	67	67	67	67	67	67	67	67	77	78	79	82
40.0	67	67	67	67	67	67	67	67	77	78	79	82
35.0	67	67	67	67	67	67	67	67	77	78	79	82
30.0	67	67	67	67	67	67	67	67	77	78	79	82

Figure 31. VE table

4.5 Fine Tune

In that paragraph the process of tuning the engine from the rough starting maps to high-performance maps is described.

4.5.1 Dynamometric Stand

To tune both VE and Ignition Advance maps it is necessary to have an ability to see how the engine reacts to changes. First of all, it is necessary to have an ability to track the power and torque curves. Dynamometric stand is the only solution for that problem. Dynamometric stand is a platform with 4 or 2 rollers to place the wheels. Rollers are connected to absorption system, which creates the load and performs the measurement. Ability to see the engine output is not the only advantage of dynamometric stand, it is also possible to use so called “RPM Lock”, which means that absorption system will lock the rotational speed of the wheels at a desired value and user will be able to tune the table precisely all along the RPM range.

4.5.2 Fine tuning the Ignition Advance

After the engine is started up successfully, it is necessary to mount the car onto the dynamometric stand and start a fine-tuning procedure. The algorithm for the performance ignition tuning is very simple. The rotational speed of the wheels is being blocked in 12 different positions according to our ignition map RPM-axis points (600, 900, 1300 etc.) and tuner starts to operate the engine on different loads according to MAP-axis. In each cell of the map ignition timing is increased until the power output starts to drop and from that point ignition angle is being reduced by 2 degrees. As a result of that process

4.5.3 Fine tuning the VE-table

Fine-tuning of the VE table is needed to reach the desired AFR around all the operational range of the engine. After the ignition advance is tuned successfully, using the same “RPM Lock” feature VE-table tune is performed. The huge difference between ignition advance and VE tune is that second one could be done automatically using the Megasquirt built-in automatic tune feature. Megasquirt analyses the reading of wideband lambda sensor and changes the VE-table in the way that real AFR matches the reference table.

5 CONCLUSION

The theoretical part of this work was aimed to examine modern engine management systems, as well as to compare them with mechanical systems. It can be concluded that mechanical engine management systems and their drawbacks were limitating factors for the internal combustion engine industry. Once the electronic fuel injection was invented, engines were not gravity-dependant anymore, became much more efficient and ecological. As a result, in course of time most major internal combustion engine manufacturers started to use the EFI technology and developed it further.

The main goal of this project was to practically study the EFI management and to build an engine control system using the open source Megasquirt platform and to connect it to an actual M50B20 engine inside BMW E36. Engine was upgraded from natural aspiration to forced induction by using a turbocharger. Most of the engine’s components were replaced to match the performance requirements. A Printed circuit board was ordered according to the official Megasquirt PCB diagram, all the components were soldered according to the assembly manual provided by Megasquirt. A wiring schematic was developed by examining the case vehicle Bosch Motronic engine control module wiring loom diagram. The module was successfully connected and after the basic settings were programmed the engine was successfully started.

During the dynamometer tuning process of the engine, an unfortunate failure of the 3rd injector resulted in immediate engine failure due to detonation and extreme local overheating of the cylinder piston. Right before the unfortunate event the car had produced 343 horsepower and 457 newton meters of torque during the fine-tuning process on the way to the maximum calculated power of around 390 horsepower. Despite the problem described above, the project could be considered successfully finished as per the fact that the engine management system successfully controlled the engine and allowed the control of all of its components, including the turbocharger which was installed during the project.

REFERENCES

HowStuffWorks (2017). *Fuel injector diagram, How Fuel Injection Systems Work by Karim Nice.* Retrieved May 28, 2020, from https://auto.howstuffworks.com/fuel-injection3.htm

HowStuffWorks (2014). *Turbocharger diagram, How Turbochargers Work.* Retrieved May 28, 2020, from https://auto.howstuffworks.com/turbo2.htm

Ihsan Omur Bucak (2010). *VR sensor and toothed wheel assembly diagram, Position Error Compensation via a Variable Reluctance Sensor Applied to a Hybrid Vehicle Electric Machine.* Retrieved May 28, 2020, from https://www.researchgate.net/figure/Variable-Reluctance-VR-sensor-that-senses-movement-of-the-toothed-wheel-past-point-of_fig1_42539593

Innovate Motorsport (2012). *Lambda installation. Innovate LC-1 Installation Manual.* Retrieved May 28, 2020, from https://www.innovatemotorsports.com/products/lc1.php

Megamanual (2010). *Components list. Megasquirt Mainboard Assembly.* Retrieved May 28, 2020, from http://www.megamanual.com/ms2/V3assemble.htm

Megamanual (2010). *Ignition Advance table creation manual. Basic tuning principles.* Retrieved May 28, 2020, from http://www.megamanual.com/ms2/

Megamanual (2010). *Megasquirt mainboard assembly. Megasquirt Mainboard Assembly.* Retrieved May 28, 2020, from http://www.megamanual.com/ms2/V3assemble.htm

Megamanual (2010). *VE table calculator. Basic tuning principles.* Retrieved May 28, 2020, from http://www.megamanual.com/ms2/

Megasquirt (2005). *Megasquirt history.* Retrieved May 28, 2020, from http://megasquirt.info/history/

MSextra (2007). *Ignition coil driver connection diagram. Megasquirt 2 V3.0 Ignition Driver wiring.* Retrieved May 28, 2020, from http://www.msextra.com/forums/viewtopic.php?f=131&t=68619

Ribbens W.B (2017). *Effects of ignition timing graph, in Understanding Automotive Electronics (Eighth Edition).* Retrieved May 28, 2020, from https://www.sciencedirect.com/topics/engineering/spark-advance

The Engineering ToolBox (2003). *Mixture quality effects graph. "Stoichiometric combustion and excess of air".* Retrieved May 28, 2020, from https://www.engineeringtoolbox.com/stoichiometric-combustion-d_399.html

TunerStudioMS (2013). *TunerStudioMS interface sample. Introduction to TunerStudioMS.* Retrieved May 28, 2020, from http://www.tunerstudio.com/index.php/tuner-studio/tunerstudioms-menu

VaporWorx (2016). *Fuel pressure control valve diagram, Fuel Pressure Regulators.* Retrieved May 28, 2020, from https://www.vaporworx.com/documentation/fuel-delivery-systems-an-understanding/fuel-pressure-regulators/

WayBuilder (2015). *Top Dead Center diagram.* Retrieved May 28, 2020, from http://what-when-how.com/automobile/conventional-ignition-systems-automobile/

What-When-How (2018). *Ignition coil diagram. Conventional Ignition Systems (Automobile).* Retrieved May 28, 2020, from http://what-when-how.com/automobile/conventional-ignition-systems-automobile/

What-When-How (2018). *Ignition Distributor Diagram*. Retrieved May 28, 2020, from https://www.howacarworks.com/basics/how-the-ignition-system-works